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Design of the upper body of a Cost Oriented Humanoid Robot

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Acknowledgment

“Wisdom begins in wonder’’
Socrates

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I thank my mother.
I thank people of Austria whom I have met, I got to know and saw them, a wonderful people.

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Kurzfassung

Die Arbeit beschäftigt sich mit der Vervollständigung eines existierenden humanoiden Roboters namens „Archie“. Dieser besteht derzeit aus einem Unterkörper einschliesslich der Beine.Die Hauptaufgabe ist einen geeigneten Nacken sowie Arme zu entwickeln wobei das Hauptaugenmerk auf Kostengünstigkeit (Cost Orientation) liegt. Nach einem ausführlichen Literaturstudium verschiedener Roboter, wurden drei, mit der bisher existierenden Hardware kompatible, Prototypen entwickelt. Bei Diesen liegt das Hauptaugenmerk auf einer einfachen Konstruktion, Leichtbauweise und gutem dynamischen Verhalten.

Hauptvorteile der drei entwickelten Prototypen sind:

- Niedriger Preis und gute dynamische Eigenschaften.
- Geringes Gewicht des Oberkörpers.
- Die Abmessungen sowie die Freiheitsgrade erlauben dem Roboter „fortgeschrittene“ Arbeiten auszuführen.

Die Arbeit beginnt mit einer Zusammenfassung der bestehenden mechanischen Struktur sowie der Software zur Regelung und Kommunikation welche für die weiteren Kapiteln unbedingt erforderlich sind.

Die drei entwickelten Versionen (V1, V2, V3) für den Nacken einschließlich der Arme werden in den folgenden Kapiteln, beginnend mit Entwurfszeichnungen bis zu konstruktiven Details, Berechnungen und Simulationen ausführlich beschrieben. Weitere zur Berechnung und Fertigung notwendige Informationen finden sich in den Anhängen. Die neuen Prototypen werden sowohl mit existierenden Konstruktionen als auch untereinander verglichen wobei die Schwierigkeit bestand aus der Literatur die erforderlichen Daten für Erstere herauszufinden. Als optimal erweist sich dabei der Prototyp V3

Abstract

The work is about completing an existing humanoid robot called "Archie". It currently consists of low body including the legs. The main task was to develop a suitable neck and the arms, having the focus at being cost-effective (cost orientation). Following a broad study of literature on the design of different robots, three prototypes compatible to the existing part were developed. With this, the main focus was at preparing a simple construction that may be easily built and have a good dynamic movement.
Key advantages of the three prototypes are as follows:

- Low price and good dynamic characteristics
- Low weight of the upper body
- Dimensions and the number of DOF allow the robot to carry out"advanced " tasks.

The thesis begins with summarised clarifications of the existing mechanical and software structure for control and communication, necessary for the following chapters. The three versions (V1, V2, V3) developed for the neck, including the arms, have been described in detail in the chapters to follow, beginning with drawings to the details of the design, calculations and simulations. Other information needed for calculation and production are available in the appendixes. The new prototypes are compared to the existing construction and with each other. The difficulty appeared to find the necessary details for the first one. Prototype V3 shows to be the most optimal.

Problem formulation

Most of the publications in this field are only dealing with simulations without an existing hardware.

Therefore the main goal of this thesis is to complete the mechanical construction of the upper part of an existing, cost oriented, humanoid robot (COHR)

This includes the design of the neck, head, arms and shoulders and the selection of the necessary components like motors, gears, controller hardware and interfaces. According to COHR it will be a compromise between price and the optimal technical solution.

Because of the constraints COHR and functionality two suggestions for the head/neck and arms will be presented in this work according to the neck, head and arms with emphasis to the kinematic and dynamic features. Advantages and disadvantages concerning, range of movements of the joints are checked and discussed by simulation results.

One of the important parts of the upper body is the neck/head where two COA 3D cameras are necessary as visual sensors under the limit conditions view range and accuracy and the price.

Therefore the main tasks of this work are:

1) Develop an optimal mechanical design for the upper part of the robot.
2) Find optimal motors, cameras and controllers for the upper body according to COHR.
3) Find an optimal hardware and software architecture, interface, motors, and communication with the lower part of the robot

Overview

Chapter 1 - This chapter is an introduction to construction of the Archie dealing with the information system of the lower part of the robot.

Chapter 2 - Special importance at robots is dedicated to interface. Here are given details on interface of biped robot, as a basis for the use of other devices during the advancement of the robot.

Chapter 3 – A view is created on the information system and general regulating of Archie through cameras, followed by the software and hardware architecture of the upper body and visual part of biped robot.

Chapter 4 - This chapter elaborates preliminary calculations that depend on dimensions and design of the low body.

Chapter 5- In this part the design of the upper body of first prototype have been given. Design of first prototype of neck/head has a combined structure, with one rotational joint and two translational joints.

Chapter 6 - The design of the second prototype of arm and second prototype of neck are given.

Chapter 7 – In this chapter we have presented the design of third prototype, which has been designed with two types of motors: Dynamixel RX-64 in arms and RX-28 in neck/head.

Chapter 8-Mathematical description of neck and arm of the second prototype is provided. Mechanical calculation and Denavit-Hartenberg parameters have been given.

Chapter 9 - This chapter studies the dynamic behavior of arm of the second prototype through the simulations, making conclusions related to the cases of testing of arm movement.

Chapter 10 - This chapter provides explanation on the moves of neck/head of the second prototype. It is provided through simulation of movement of head/neck design and models built with Simulink tools in Matlab.

Chapter 11- This chapter shows properties of actuators of the arms of prototype three, marked shortly as V3. In addition, simulations of neck/head and arm have been presented in order to show performance of the movement.

Chapter 12-This chapter provides comparison between the three designed versions; V1, V2 and V3, their advantages and disadvantages, mass distribution on robot body and the basic characteristics of the design.

Chapter 13 - Provides the proposals for the work in the future.

Appendixes A, B and C - Includes all the parts that constitute the design of the first, second and third prototypes

Appendixes E and D. Mass properties and moments of inertia and arm and neck of the first and second prototypes have been given.

1 System information

“What I cannot create, I do not understand”
Richard Feynman

1.1 Introduction

Archie has its history. During this period various forms of design of legs, feet, joints and waist, changing the shape, dimensions and motors were tested and experimented. By adding motors to legs and by changing the shape of the waist, the dimensions have changed in length too. There are also proposed different algorithms for adjustment of stability, the way of robot orientation, and there are given various works on kinematics and dynamics of existing part (the lower body). Archie lacked the upper body, although the design of the upper part was proposed in previous works, taking as base the dimensions and height of the then existing part. With the change of height in the lower part, changes occurred totally in all lengths of the upper part too.

Recently, in 2014, a link and actuator were added at the part of legs, for each leg, thus increasing its length. The upper part of the robot includes: upper limb, neck/head, the back where many electrical devices will be mounted, including the main controller, and the sensors. The design of the neck/head has been designed in three prototypes; design of the first prototype including a serial neck, where it is built only by rotating joints, and the design of the second prototype that includes a combined neck that consists of a rotational joint and two translational joints The design of the third prototype includes a serial neck, built only by two actuators. All necks have a platform where cameras are mounted, being at the highest point of robot body, and they represent head of the robot.

Arms and chest where robot shoulder is connected include an important part of the design, so that the design must be connected at thorax of the existing part, that way all this part is then mounted on the back of the robot. Following the measurements, three prototypes of arms were designed, one of them is more advanced than the other regarding movable range of joints as a result of complexity of the parts that were designed, and for the position of joints that will move the arm. The distribution of mass in the whole robot is very important; attention must be paid to distribution of mass on the upper part.

The prototype of a more advanced design can be used with further advancing of robot Archie. The upper body should be a continuation of the lower existing part, thus being like a condition which shall limit the design of the upper body. This design should include not only the same material of the lower part the robot is built of, but also should have the same view, and the same nature of design. Such issues are taken into consideration during the phase of design. Mechanical tests include various simulations that should be done to design the neck/head and arm, seeing closely behaviours of the mechanical design.

Hardware is an important part of the design and must be completed. In fact the design cannot begin without deciding on the type of cameras, type of motors that will be mounted in the skeleton of the robot. Upon deciding on type of cameras to be used, and about motors for the upper part of the robot, the devices for the lower part must be taken into consideration also, including their interface and compatibility of used ports. Recognition of properties of interface is an important part of the system of information.

Upon explaining the information system, it is impossible to avoid giving the appearance of hardware and software architecture. In the case of choosing cameras, it is needed to take into consideration all above mentioned features. This helps in creating the general view of hierarchical organization and functioning and the design of the upper part which will be presented below.

1.2 Hardware and software

This chapter shall provide a description of the architecture of Hardware and the interface of Archie. Ways of communication of this equipment, general properties, the functions and tasks completed by the robot. Processors of control play an important role in the hardware part, carry out fast data processing. Then the other part is that of memorizing of this data that is stored to be processed later, retaining a special role in electronic device, to have the robot functioning in real time. In this chapter, particular attention has been paid to another role of hardware architecture, and that is the interface, and it consists of the following; ports, speed and amount of bus load.

The interface foresees the type of connection ports and the space for data storage and processing and transmitting features such as high bandwidth and the speed of transmission and compatibility.

The ability of the highest possible interaction of the main controller responds to all electronic devices in the robot such as; motors, sensors, and interface between them, thus enabling data processing and real time transmitting. It has also been indicated that any new prototype of the robot, after proposals that have been made, requires changing of the overall interface. Number of devices is sufficient for optimal dynamic system of the robot; to ensure motion of mechanical structure of the robot and its control.

The type of camera connections proposed is in line with the ports of the main electronic board. The ports are of the following types: USB 2.0 and USB 3.0 and CAN bus. The nature of functioning and their technical features have been described.

The increase in the number of devices such as electronic board and sensors is in function of further advancement of the robot, namely the control system. The addition of other sensors and controllers will be conducted in accordance with the existing lower part of the robot.

Actuators functioning and technical attributes of ports through the devices have access to the network such as; USB 2.0 and USB 3.0 and CAN bus. Details of the hardware features and nature of connection, and in general the function of CANbus have been described. Showing that Archie communicates with the main controller through CAN (Control Area Network) with Linux operating system where C++ software is installed.

The robot consists of hardware and software architecture. It is obvious that the hardware architecture available determines the software that will be used. Our efforts to make the Archie fully autonomous are related to hardware, and then with implementation of software.

One of the most important points in the hardware architecture is the overall calculation of energy that is spent by robot. Undoubtedly, from all devices such as cameras, sensors, actuators, Elmo Controller, main electronic board, the largest consumers of energy are the motors. Robot is a data processing machine executing its work by its movement. Source of data comes from Hall sensor, cameras and other sensors. This data is of different natures, the image comes from camera as input, while signals of dislocation position of bobbin magnetization in the motor come from hall sensor, they are directed by the software part, comparing the input and output values in general. For example, electrical motors are different as regards to the following characteristics: brushed and brushless DC motors and other sensors too. Hence, it derives that various devices have different requirements for processing the data brought to the main board. Final data processing is done in the main controller.

1.3 ELMO Controllers

Controller of Archie is an electronic device produced by ELMO Motion Control, mediating the main controller and actuator. Motor power supply is also provided through ELMO controller. ELMO controllers and main board generate synchronized pulses and process data through sequences of instructions by the program. The controller houses a system clock where a waveform pulse is generated, this pulse has three features; increase of impulse, decrease of impulse and the second increase of impulses, representing the length of a cycle and the end of the first cycle and beginning of the second cycle. Inside the controller there is a cycle of time synchronized signal.

There are two actions occurring in the processor; read and write. With ‘read’ we understand the orders received from external sensors (as cameras) and internal sensors of the robot (such as Hall sensor that reads the position or angle relocation of the motor and speed).On the other hand ‘write’ denotes the execution of orders after receiving the information about the status in order to bring that system to another desired situation.

In digital speech it is expressed in binary state; 0 and 1. The state 0 denotes voltage low values and 1 denotes the high value of voltage. Differently, they can be called logical ‘true’ values (high logic level) or ‘false’ (low logic level).

Logical circuit is an electrical circuit, which at the input takes the signal in the same way of a pulse waveform and changes it at that input, into another pulse in the output (Xie, 2002). These processing actions occur in Arithmetic computation (ALU-arithmetic logic unit). Processes are carried out at a higher level in the processor of the main controller.

1.4 Information System

The mechanical design would have such a form as to ensure dynamic stability. The hardware part would create sufficient memory for data storage and powerful processor for data processing.

There are 13 controllers, likewise that many actuators, at the existing part of Archie, and it means that every actuator has one microcontroller. The thirteenth actuator at the part of torso will activate for movement of the back bones, after assembling the upper body (Fig.1-1, actuator marked with number 13).

Current number of actuators will be 26, following construction of the upper body, as per design of the first and the second prototype. After construction of the design in accordance with the third version (V3), the total number of actuators will be 23 (13 actuators for the Low body+10 actuators for the Upper body). In case of redesign of the electrical part, the number of microcontrollers may be reduced.

Elmo controllers mediate communication from the motors to the main controller, taking and providing information through data communication.

1.5 CAN BUS

ELMO controllers are responsible for the control and taking the correct values about the situation of actuators. All ELMO controllers are connected at the main electronic board; through CAN (Fig.1-1). Every ELMO controller controls a motor. While the highest level will be electronic board, while PC will act as host, a PC for interventions in electronic board. (Elmo Motion, 2008)

Every motor rotation speed and angle positioning of motor shaft is measured. Servo controller communicates directly with Controller, while ELMO controllers communicate with the main controller through CAN bus. Two wires of CAN bus connect controllers in serial manner in one leg, in the same way it applies also for the other leg connecting with CAN converter, which in output has the USB 2.0 port sending the information to the main electronic board. The main controller has been proposed in order to make the robot as autonomous as possible, so that it plays the role of robot 'brain' where all information is processed from the lower part to the upper part of the body.

Elmo motion Control Company has provided information about production of Elmo controller has the ports which are *non-isolated*. (Whistle and Tweeter, 2014) CAN open of the robot, version DS 301 V4.01 is interface of Archie, through the largest part of robot devices communicate, including actuators, and the force sensors are planned (Elmo Motion, 2008). Connection of CAN Controller and ELMO controller and the conductors constitute the CAN bus. Number of pins of the controller where CAN bus is connected are; 20- CAN_GND CAN ground, 21- CAN_L CAN_L , 22- CAN_H CAN_H .

CAN open consists of; application layer, presentation layer; session layer, transport layer, network layer, whereas CAN bus includes Data Link layer and Physical layer.

Amongst the features of CAN bus, it is I-7565 converter is completely compatible to ISO 11898-2 standard. This standard is characterized by data rate to 1 Mbit/s with a length of cable up to 40 m. Delay of data distribution in this length of wires is 5 ns/m.

Cable consists of two conductors, usually the conductor CAN_L is with lower voltage the other conductor is higher voltage CAN_H, with impedance up to 120 ohm. Variation of the voltage between the two conductors of bus is up to 5V. Conductor cross-section of the robot CAN bus is 0.25 mm^2, length related resistance is 70 mΩ/m. The number of controllers connected to CAN bus is limited by size of busload. To be compatible with all controllers, similar bit-timing is used.

Table 1-1 CANopen features (Elmo Motion, 2008).

Some features	CANOpen
Baud rate	50 kbit/s-1MGbit/s
Interpreter method	Binary or ASCII
Fast referencing	Yes, for PVT
Network of servo drivers And Multiple servo driver synchronization	Yes
Standardization	Compliant with CiA standard
Special equipment required	CAN communication interface (available as an add/on ISA or PCMCIA card for PCs) with appropriate software
Software	ELMO Composer program.

Voltage of conductors and data transmission speed varies by size, the longer the length, the transmission speed tends to fall. CAN bus features of Archie, according to the company producing the I-7565 converter, with 82C250 transceiver type CAN, are given in Tab.1-1, (Elmo Motion, 2008). Based on the description in the document for the features of CANopen for Elmo SimplIQ servo drive, program from ELMO Control Company;

Physical layer is a standard for serial communication where coded data is transferred into electrical pulse through two wires have variations of voltage. Devices that are part of Physical layer include CAN controller. The device mediates transmission and reception of data through CAN controller and bus consisting of two wires being a CAN transceiver. This way, for the body of the robot, (including the lower and the upper part) length of 25 meters of bus is sufficient, working in a maximum speed of communication between the equipment and main controller and PC (CAN Bus, 2013) . While the number of servo drivers that can connect in this length, without affecting the speed value of transmission is 25 to 30 servo drivers. The following table presents dependency between length of bus and speed of communication by Elmo SimplIQ digital servo drives, provided by the company Elmo motion control, (Tab.1-2), (ICP DAS, 2013).

Data link Layer transfers messages from the motor through ELMO controller to the bus without errors. So, after it sends messages using bit stuffing and bit checksums, it does not conclude its shipment up to that moment when it takes information from main controller, that its message is entirely accepted.

Table 1-2. CAN Bus features, Speed & Distance (ICP DAS, 2013).

Baud (bit/sec)	Ideal Bus Length
1M	25
800K	50
500K	100
250K	250
125K	500
50K	1000
20K	2500
10K	5000

1.6 Communication in CAN open

The message consists of; function Code+Node ID+Data Length+Data (consisting of 8 bit). Hence, it must be noted that RTR, remote transfer bit, is not supported by ELMO driver (Elmo Motion, 2008). In this composition, the necessary information is given within the message, concerning the functioning, ID of the message as to node it will belong to, and the content of the data too.

As an example, the following can be highlighted, COB-ID of PDO1 taken as a binary number 01000000010 from node number 2, being 202 hexadecimal.

Master CAN open is the main controller. The main controller sends the requesting message to the network, while seeking the data to comply with the request of the main controller, using ID of this message to identify controller, requesting information. Thus making communication safer and without crashes in the bus. The designated controller sends its demands through SDO client from the server; this is achieved by submitting CAN-ID of 600+ Node ID of ELMO controllers. Server responds with CAN-ID 580h+Node ID. Thus using in communication always respective ID-s of controller, so that the communication is known.

The moment the main controller sends a message through CAN converter to network, it represents SDO client, all ELMO controllers 'see' the message. But, certain nodes are going to take a message with ID 603h understanding by ID that this message is dedicated to it, responding with ID 583. Object dictionary makes interface between protocol and the application software (National Instruments, 2013)

Furthermore, OD includes the range from 1000h to 1FFFH so that communication of some of the participants in network can be arranged and configured, and at the range from 2000h to 5FFFh and from 6000h to 9FFFh the specifications of the producer or to choose the standard manner can be provided.

The mechanism for detection of errors in CANbus, detects error in bit level applying three ways.

1.7 Brushed DC Motors

Brushed Motors parts of the Archie are produced by Faulhaber Company, of DC Micro-motors type. The table provides some features, in temperatures of 22 Centigrade and of nominal voltage, with power 73mNm, with mass of 242 grams. Size of this motor covers a diameter of 32 mm, length 57 mm, with graphite commutation (Technical Information (Faulhaber), 2016). According to technical data from Faulhaber Company, brushes are made of graffiti, while commutator is made of copper, ensuring appropriate functioning for applications with high power, as well as rapid start up and stoppage the robot needs. Brushed DC contains housing in Stator covering the motor, permanent magnet and brushes. The commutator is fixed on the shaft and magnetized through windings.

The remaining part of harmonic drivers includes; planets, internal gear, ball bearing, output shaft, then the inner shaft, and through gears transmits the torque into output shaft etc. Brushes are connected to two conductors that conduct energy to the brushes.

Table 1-3. Properties of the motor (Technical Information (Faulhaber), 2016),

Values at 22 C and nominal voltage	**Value**	**Units**
Nominal voltage	24	V
Terminal resistance	1.63	Ω
Output power	83.2	W
Efficiency, max	83	%
Stall torque	539	mNm
Speed constant	253	Min^{-1}/V
Torque constant	37.7	mNm/A
Current constant	0.027	A/mNm
Shaft bearings	Ball bearings, preloaded	
Speed up to	7000	Min^{-1}
Number of pole pairs	1	
Mass	242	g(gram)
Housing material	Steel, black coated	

Actuator is connected to ELMO controller with two wires that feed the power. While with ribbon cable through 6 wires it is connected with the part of control. Commutator consists of segments made of copper sleeve, attached thus enabling transmission of electricity in the windings. Thus, with the slide of the brushes over commutator the electricity is followed to windings magnetizing them.

The speed of actuators is approximately in proportion with the voltage applied on it. The speed control applies cascaded position control. The signal pulse-width modulated signal is used to generate an average voltage.

Windings serve as low past filter, so PWM with a sufficient frequency will create a stable power, (Technical Information (Faulhaber), 2016). Motors have constant stator field. The change of voltage value is associated with the change of the speed of rotor's rotation, so the ratio voltage and speed is quite linear. Hence, the current draw depends on the rotation moment in the shaft. They have some disadvantages, one of them is amortization of brushes, and it creates noise. Some properties of the motor are given in the following Tab.1-3 (Technical Information (Faulhaber), 2016), with gears 415:1 of the power of 83.2 W when the motor works under nominal voltage.

The figure (Fig.1-1) provides brushed DC actuators with numbers 11 and 12 located in the rear part of the robot, making the movement of torso more flexible, while at the front part their whistle micro-controllers are mounted. The B marked part, in the cylindrical shape represents the "back" of the robot. Brushed DC motor with number 13 is mounted and harmonic drive through the geared belt is connected to the geared wheel enabling movement of the cylindrical part (the back of robot). After construction of the upper body part, brushed DC motor will be activated with number 13, giving 1 DOF with minimal angle shift + /- 10^{o}.

This shift of the motor 13 makes the movement of the upper body of the robot, and such movement may occur in the same coordination with the moves of the neck when the robot turns the head based on its attention.

Similar with the movement of humans, upper body move is slower than the neck movement when the head turns in direction of scene.

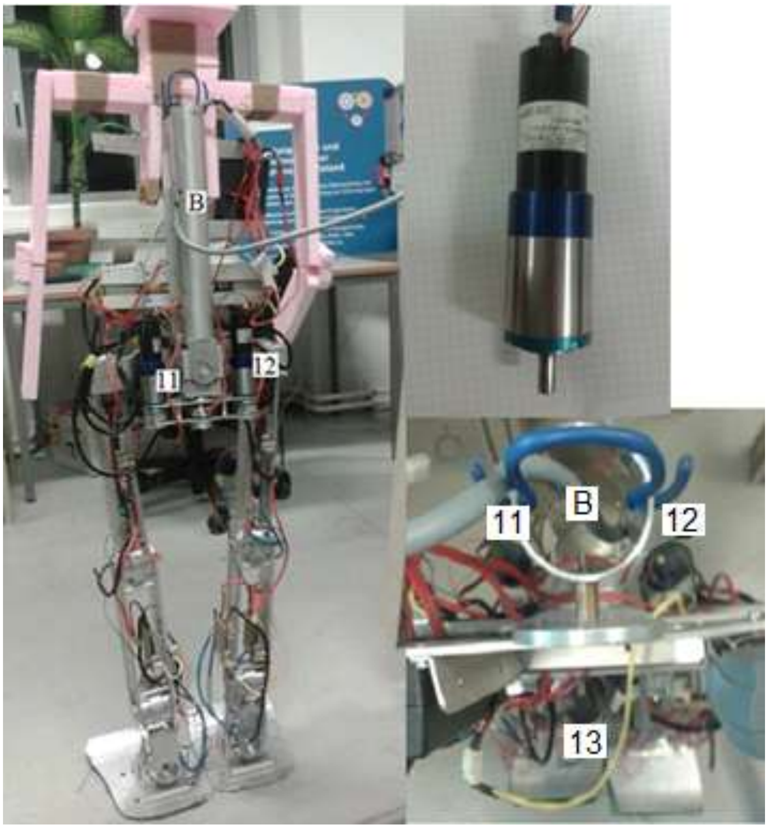


Figure 1-1. The torso

1.8 Features of BDC Motor

The part of the pelvis contains 3 brushed DC motors; they are installed in orthogonal way on the triangle platform of Pelvis of the robot. This five angle platform consists of two plates, of the same size, parallel, in that distance that provides the space for the geared belts to link with the geared shaft creates the movement. It should be noted that one of motors is inactive. Motors produced by Faulhaber Company, of DC Micro-motors type, the following Tab.1-4 provides some features, in temperature of 22 centigrade and nominal voltage.

Table 1-4. Brushed DC Motors (Technical Information (Faulhaber), 2016).

Out power	P2nom	83.2	W
No load speed	no	5900	1/min
Torque constant	kM	37.7	mNm/A
Shaft bearings	Ball bearings, preloaded		
Rated Torque	MN	71	mNm
Housing material	Steel, black coated		

1.9 BLDC Motor

The biped robot consists of 10 Brushless DC actuators (2 brushed DC actuators) that connect the links, 5 BLDC actuators plus 1 Brush DC motor for each foot. Each motor is a joint and connects 2 links built from safety aluminium, securing a DOF.

Servo motors of Archie consist of Brushless DC motor, gear reduction drive for torque increase. Another very important part is the Servo motor control circuit, and encoder has to indicate the position of the rotation shaft of the motor. Method of control at Brushless and Brushless DC motors must have special controller. The Controller works through magnetic induction on the side of BLDC motor where the encoder is found where conductors are connected with 7 conductors while on the other side there are 9 wires that are connected with Elmo Controller, for command and supply of electrical energy to motors. Actuators are equipped with encoder that counts the rotor rotations. Robot actuators are provided with encoder hall sensors that evaluate velocity for control feedback loop. Winds are found in the Brushless DC motor of Archie, more specifically they are located in the stator and they are of 12 poles (Technical Information, April 2015), while the rotor has a permanent magnet.

The output shaft of a servo motor is commanded to move in certain angle positions. A certain angle displacement of a robot joint gives a movement, knowing the position of displacement of shaft by sensing position and checking it with control circuit; the robot will control its movement. It should be pointed out that 3 Hall sensors are in the distance of Brushless motor investigating the position of winding magnetization. For each servo motor, there are instructions predefined in the program to move actuators, knowing the position of angle repositioning of their shafts and by controlling the size to what they will be repositioned. In Fig 1-2, below legs of the robot are given, where

ELMO controllers are mounted, and the motor positions can be seen too. It indicates the area between two rectangular sheets made of aluminium and electric conductors.

Numbers 1 and 2 mark Elmo controllers with sufficient space for the electrical part, A and B are Brushless DC motors at the bottom of the leg. The controller with the number 1 is placed outside the alloys to create space on the connection of conductors. Links are made of two couples of sheets (fixed to both sides of the Brushless DC motor), providing space between them for placing the micro-controllers ELMO mounted in their PCB (Printed Circuit Board).

The view of pelvic of the robot, marked with *A* brushless DC motors and with *F* brushed motors (mass of brushed 3x 600 gr =1800 gr), the rotation shafts forming the angle of 90. C marks the gear belt that links to the shaft also geared that are fixed mechanically to *B* motor, driving it along with *A* motor (Fig 1-3). Archie has a motor in each joint with a harmonic drive to enable the movement in every joint under control of an Elmo motion controller. The controllers take signals from low level led by the highest-level of PC**.** Just to have it clear, the rotors' angular position or position of electromagnet pole, through feedback signals to control semiconductor switches. To get feedback signals, different sensors are used. In the case of Archie actuators, Hall sensor is utilized and works based on Hall Effect from where it has taken the name.

Figure 1-2. Lower limb

Whenever they are near the sensor, the magnetization of windings gives a high or low signal indicating that it is the North or South Pole of magnetization.

Magnetic fields from windings cause a pulse in the hall sensor, this pulse is taken as an absolute value of magnetic rotary encoder, and thus the read position of the motor shaft angle is directly given through a binary code taking values from 0000 to 1111.

Figure 1-3. The pelvis

Key advantages of sensor are; no wearing of mechanical parts, easy interfacing the analogue input, Digital Halls – up to 2 kHz (Technical Information, April 2015). Hall sensors are attached to the plate where the bobbins of the stator of motor are fixed and at the same location the electronic board (PCB) extends where electronic circuit of interface of motor controller is stamped. Hall sensors are with quite small dimensions, that is why their use is practical at brushless motors near the windings of the stator, and they are quite resistant.

At Fig.1-4, the sensors have been marked with capital letters A, B, C fixed at motor stator. Stator of Brushless motor EC 45 flat ∅ 42.8 mm (Technical Information, April 2015), number of pole pairs 8, of 3 stages, from 12 windings in the stator, and with permanent magnet in rotor.

Figure 1-4. Stator of Brushless motor

Windings are in the stator of motor, every stage has four bobbins (4x3=12). The current in windings of stator is done through electronic commutation based on the rotor position. Permanent magnet is integrated in the rotor.

1.10 Summary

This chapter provides details on the existing part of the robot (low-body), on the technical features of functioning of the equipment. In creating the design of the upper body, it is necessary to study the devices to be installed on the robot, such as; controllers, actuators, cameras and interface of the software. Knowing the structure of the lower body interface, information system and design gives us the possibility of continuing with the upper body.

The view of the way of communication has been provided, and the role of functioning devices organized in a hierarchy in the lower and the upper level. Explanation has been expanded by indicating the software architecture based on how they work, showing the organization of functioning, individually for each actuators and controllers. This chapter contains diagrams showing the manner of automatic adjustment of the entire Archie.

Number of controllers can be reduced, replacing them with new controllers of a type to enable controlling more actuators per controller, and thus the structure of information system would be simplified.

2 Interface

"Nature uses as little as possible of anything"
Johannes Kepler

2.1 Introduction

This chapter explains the specifications and characteristics of Archie interface. Nowadays loads of texts have been compiled in regard to robot interface and the technical specifications of interface. The production of ports with varying characteristics provides communication of equipment with performance possibilities. Robots' advanced interfaces are by characteristics and the speed of the great quantity of data transmission in short time intervals.

2.2 CAN converter

I-7565 called by the producers as intelligent USB to CAN Converters enables communication of PC with robot. This device has two ports; one port for interface with CAN bus, while the other for standard type of USB slot. Interface opportunity is available at every PC and is supported by Windows operating systems (98, 2000, XP) and Linux.

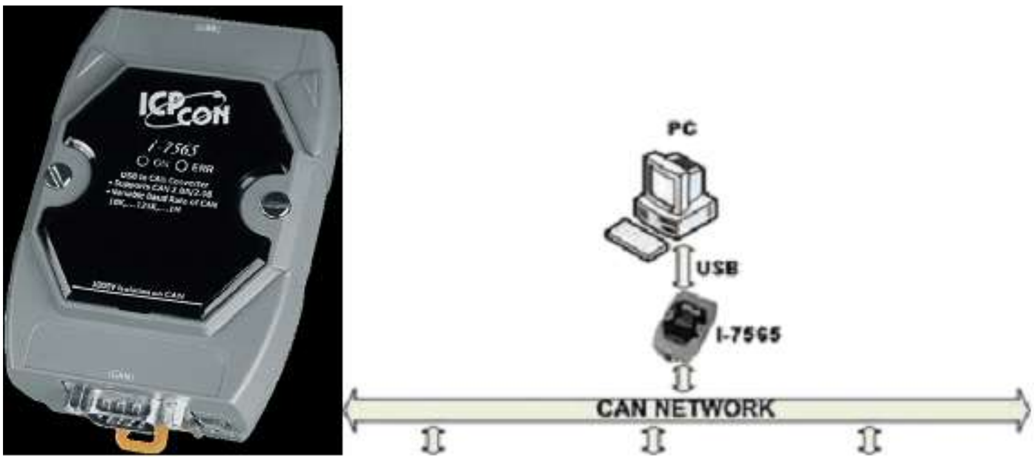


Figure 2-1. The device I 7565 and CAN network (Data sheet; IndustrialTech, 2013)

With the installation of the I-7565 into PC, relevant device drivers are automatically downloaded and installed, and then communication starts with USB interface, creating access in CAN device through tool or users' application. CAN converter can be used in control system, vehicle system, factory automation etc.

On one side CAN converter to USB is a CAN port connected with wires of CAN bus while on the other side it is a USB port. CAN converter is powered by the USB bus (Fig 2-1).

On the left side there is a view of the device I 7565 and on the right side there is a ling of this device with CAN bus and with PC through USB cable type A to type B (ICP Das (i-7565 Manual), 2007).

. The diagram shows the manner of communication and internal data exchange I-756 from CAN to USB driver. In the centre of microprocessors is installed for processing the data, Fig.2-2.

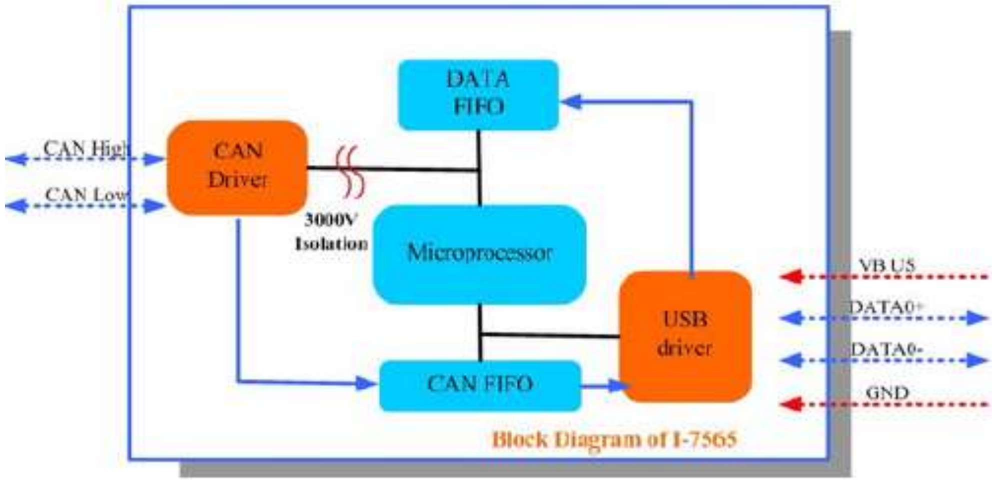


Figure 2-2. The function of I-7565 converter (ICP Das (i-7565 Manual), 2007).

In the table (Tab.2-1) of the main features of I-7565 are given.

Speed of communication of CAN converter is 921.6 Kbps fixed for USB. On the side where CAN bus is connected, the speed is 1 Mbps max. CAN D-Sub has 9 pin interface connector, with dimensions; wide-123mm x L-72mm x-33mm high. USB cable type A to type B (2.0), on one side has the type A USB plugs in PC whereas on the other side of the cable there is a type B USB plugging in I 7565 device. CAN port of I-7565 has insulation of 3000 V to protect the device from damaging signal coming from CAN network. I-7565 is equipped with a watchdog that monitors during operation.

A watchdog is a circuit of hardware protecting automatically from software anomalies and resetting the processor, when it works in any noisy environment. Output of watchdog timer resets the signal of microprocessor, whereas the processor restarts watchdog timer's counter (Barr, M., 2001).

From the circuit in Fig 2-3, it is clear that CAN transceiver is a mediating device, carrying differential signals from CAN Controller to CAN BUS line. At the beginning it was built for use in cars, broadcasting high speed applications up to 1 Mbaud (Data sheet PCA82C250, 2011).

Table 2-1. Features I-756 from CAN to USB driver (Data sheet; IndustrialTech, 2013)

Hardware	EEPROM: 2 KB (for system information), 100,000 erase/write cycles
Interface	Port Channels: 1
	Transceiver: Philips 82C250
	Connector: 9-pin male D-Sub (CAN_L, CAN_SHLD, CAN_H, N/A for others)
	Baud Rate: 10 k, 20 k, 50 k, 100 k, 125 k, 250 k, 500 k, 800 k and 1 Mbps
	Isolation: 3000 Vrms on the CAN side
	Terminator Resistor: Selectable 120 Ω terminator resistor by jumper
	Support Protocol: CAN 2.0A/2.0B
	Receive Buffer: 1000 data frames
	Max Data Flow: 250 fps
UART Interface	Connector: USB Type B
	Baud Rate: 921.6 kbps fixed
	Compatibility: USB 1.1 and 2.0 standard
	Receive Buffer: 900 data frames
Power	**Power Consumption:** 1W
LED	Round LED: ON LED: Power and Data Flow; ERR LED: Error
Mechanism	Installation: DIN-Rail
	Dimensions: 72mm x 112mm x 33mm (W x L x H)
Environment	Operating Temp: -25℃ to 75℃
	Storage Temp: -30℃ to 80℃
	Humidity: 10~90% non-condensing

The 82C250 CAN transceiver is marked as PCA82C250 and conducts the interface of CAN protocol controller with physical bus.

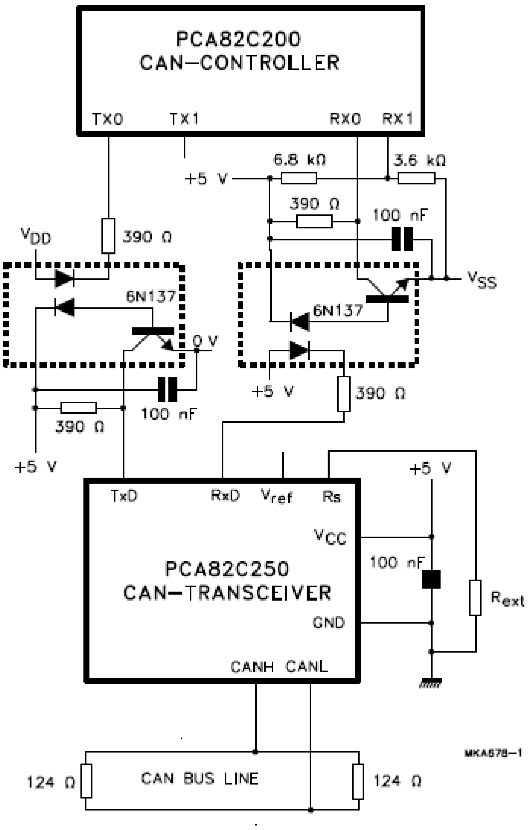


Figure 2-3 Application of the CAN transceiver (Data sheet PCA82C250, 2011)

2.2.1 Architecture of I-7565

The diagram given below explains the architecture of software of I-7565 where this software participates in carrying out the work of the device;
ASCII sends the messages in string format, so the I-7565 receives the messages converting into CAN messages distributing them into CAN network.

CAN message through I-7565 is transferred into message using ASCII strings forms through USB port, it further continues into USB cable heading to PC (ICP Das (i-7565 Manual), 2007). The messages in ASCII strings format are converted by converter (I-7565) into CAN messages enabling them to broadcast the messages in CAN network, as seen in the diagram in Fig. 2-4.

- The OPC server (Open Platform Communications) is software of Microsoft enabling Windows OS programs to communicate with the device. The hardware communication protocol converts by enabling the use of PLC (Programmable Logic Controller at industrial computers controlling hardware devices). Open Platform Communications is a feature of real time data communication through control devices of various producers; it is a standard interface software and industrial telecommunication feature. (OPC Datahub, 1995 - 2010)

- ASC II command sends and reads the data and receives information on the status from the device.
- CAN ID data is obtained from CAN convert using Virtual CAN Kernel and Application programming interface (APIs).

A USB virtual COM port is software to enable applications to have access into USB device. USB virtual COM port devices serve as a pathway connecting USB and asynchronous serial interfaces. However, some COM -port convert USB data and parallel USB interface (Fig.2-4) taken from (Data sheet; IndustrialTech, 2013). The data is read and stored by on-chip analogue port and then is sent via USB to the microprocessor (USB Implementers Forum, Inc).

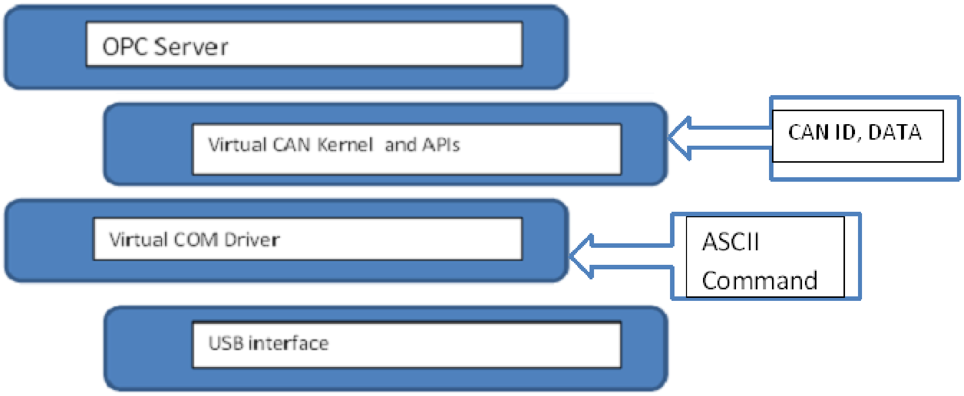


Figure 2-4 Software architecture of I-7565 (Data sheet; IndustrialTech, 2013)

2.2.2 Hardware connection I-7565

The D-sub-miniature (D-sub) is a type of electrical connector. It is called so because of the shape of letter D. The CAN BUS port connector is 9 pin D-SUB male. The connector has metallic vesting for its protection (ICP Das (i-7565 Manual), 2007). It consists of two rows of pins. Connecting of CAN bus with connector D_sub is done through pins; pin number 2 marked as CAN_LOW (CAN_L), and pin number 7 marked as CAN_HIGH (CAN_H). The pin assignment of the CAN port on the I-7565 (DB9 male) provided at the left side of Fig 2-5 (ICP DAS (i-7565_wire), 2013).

View of the port I-7565 at the part where CAN Bus is connected (on the right side) of the port D-Sub male 9 pin (on the left side, a pin assignment has been provided). In our case, at Archie, it is connected to pins 2, 7, and pin number 5, marked as *nc*, or CAN_SHLD, can be set to GND.

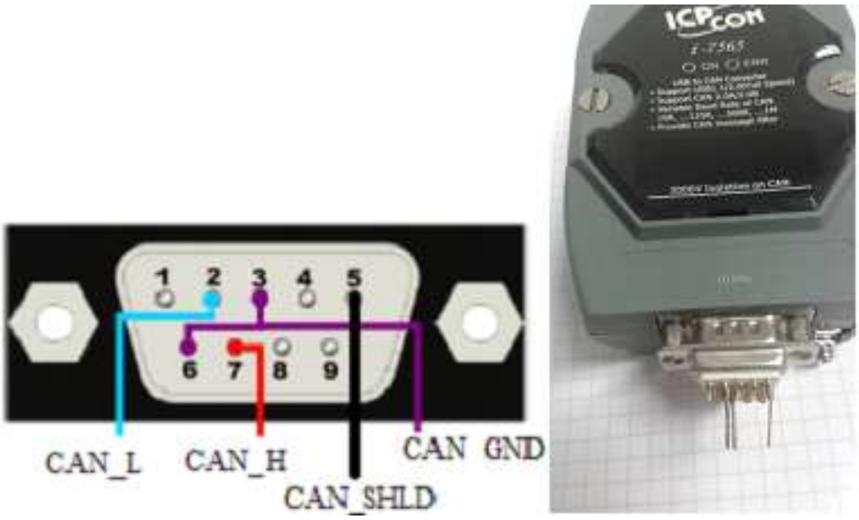


Figure 2-5 View of the port I-7565 (ICP DAS (i-7565_wire), 2013).

2.3 Specifications for CAN bus

According to ISO 11898 specifications, CAN bus has 2 differential wire interfaces which can be; shielded twisted pair, Ribbon cable or unshielded twisted pair. Can bus of Archie has 2 wire unshielded twisted pairs. The couple of wires CAN-L and CAN-H begin by connecting into a resistance of 120 Ohm on one side of CAN network, and they end connected to another resistance of 120 Ohm on the other side. As we may see in Fig.2-6, the two wires, on both sides, at the beginning and at the end, have the resistances. Cables connect an ELMO controller to another in series (Fig. 2-6). Type of cable is 23AWG (American Wire Gauge, a U.S. standard set of wire sizes) while the transverse cutting of conductors is (0.25 ~ 0.34mm^2)' cable resistance/m about 40 mOhm (ICP Das (i-7565 Manual), 2007).

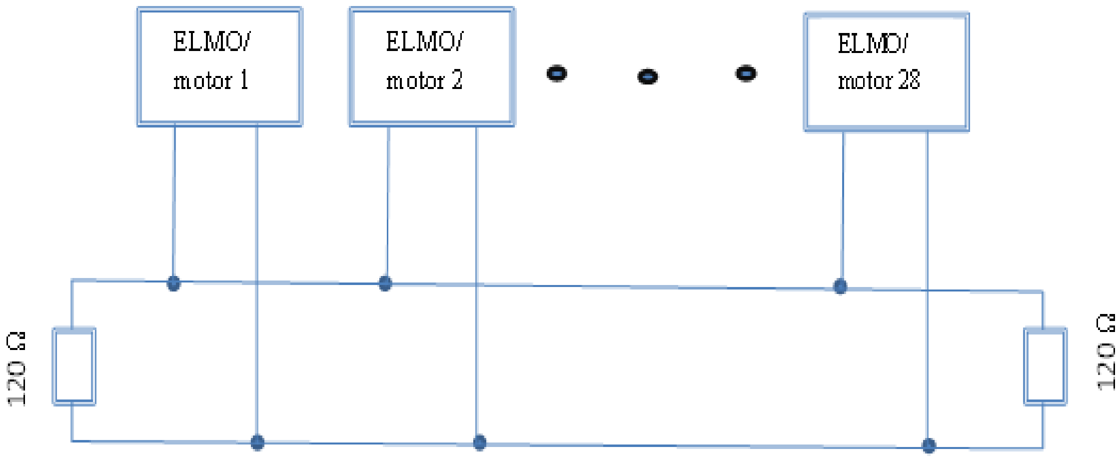


Figure 2-6 CAN Bus network terminated (adapted (ICP Das (i-7565 Manual), 2007))

2.4 Organization of interface

Main controller of biped robot central main computes connecting in micro-controllers, sensors and cameras. Electrical board receives the data in form of signals, stores and uses it for checking the current situation of the device, and the state we want to have.

Sensors require certain bandwidth and cycle time. The cameras have a high requirement for bandwidth compared to requirements of actuators, whereas cycle time must be for cameras about 20ms (Regenstein & Dillmann, 2003). So, sensors (sensors are proposed) and cameras are source of data for controlling the robot.

In the following figure, we have provided a block diagram (Fig 2-7), that makes a general description of biped robot interface. In order to describe the type of interface between devices constituting the robot, with CAN bus playing the main role.

The information system of the robot consists of the low level that is micro-controllers with the actuators, having I/O (input - output), according to the tasks and responsibilities dealing with data processing. Understanding and the principle of work of I/O system is important for control of the robot. Micro-controller decides for the speed, the position and direction of actuators, cannot guide the actuators directly because of the limited electrical power (current and voltage) they have in the output.

Every respective micro-controller of the robot cooperates with communication side on the main board. Consequently, the main controller, in order to control and dictate the state of actuators, supporting with required energy and information for precise movement.

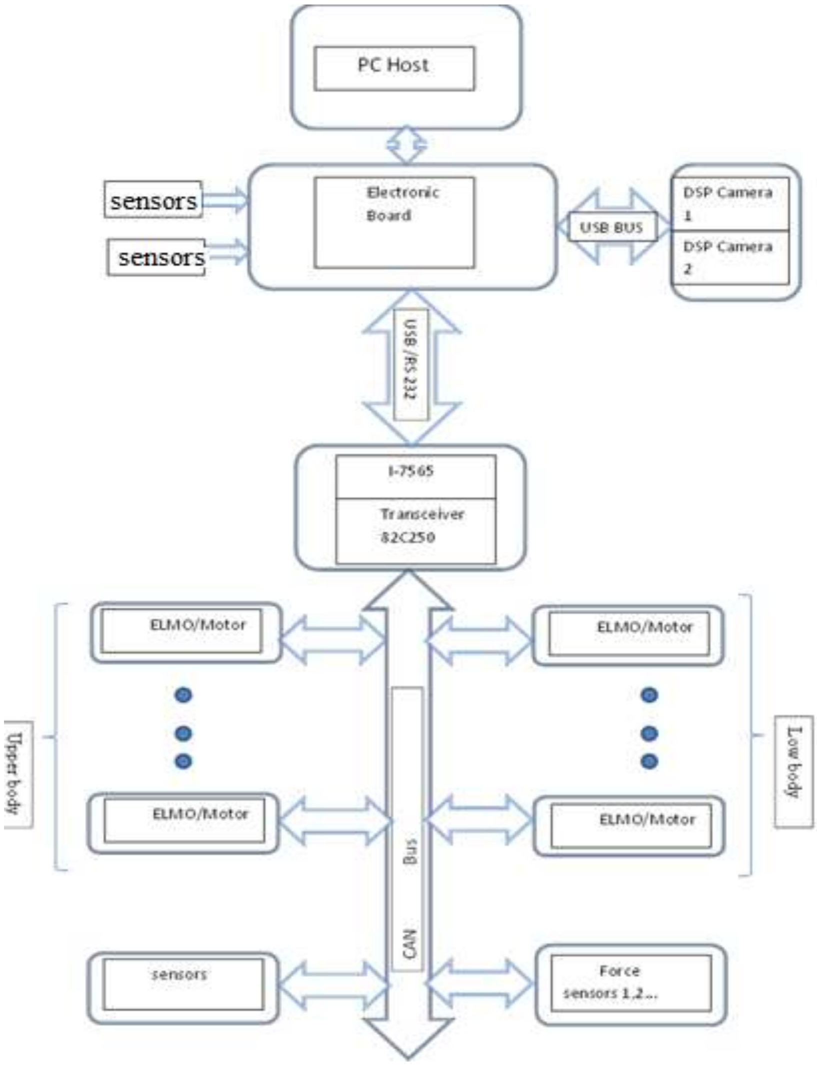


Figure 2-7. Block diagram of architecture.

2.4.1 Interface CAN bus

Archie in each joint has the motor with harmonic drive to enable the movement. Each joint move under the control of an Elmo motion controller, all the Elmo controllers are linked with the highest level of PC command. Elmo controllers are connected to a series by two conductors of control area network (CAN). Every motor has its own ELMO controller connected with PCB that is integrated in it.

ELMO controllers are supplied by a switch, from 3 couples of wires coming out for supply of energy; one couple is for 2 ELMO controllers that are connected to brush DC motor connected in series.

CAN master or client transmit message of request to another controller to respond to its command, so CAN slave or controller responds to the request according to requested issue, and vice versa, thus creating the master and slave link.

All messages sent by servo drive are marked with their ID. Thus interface through CAN bus and manner of communication by principle of the protocol CANopen of biped robot looks like in the block diagram in Fig.2 -8.

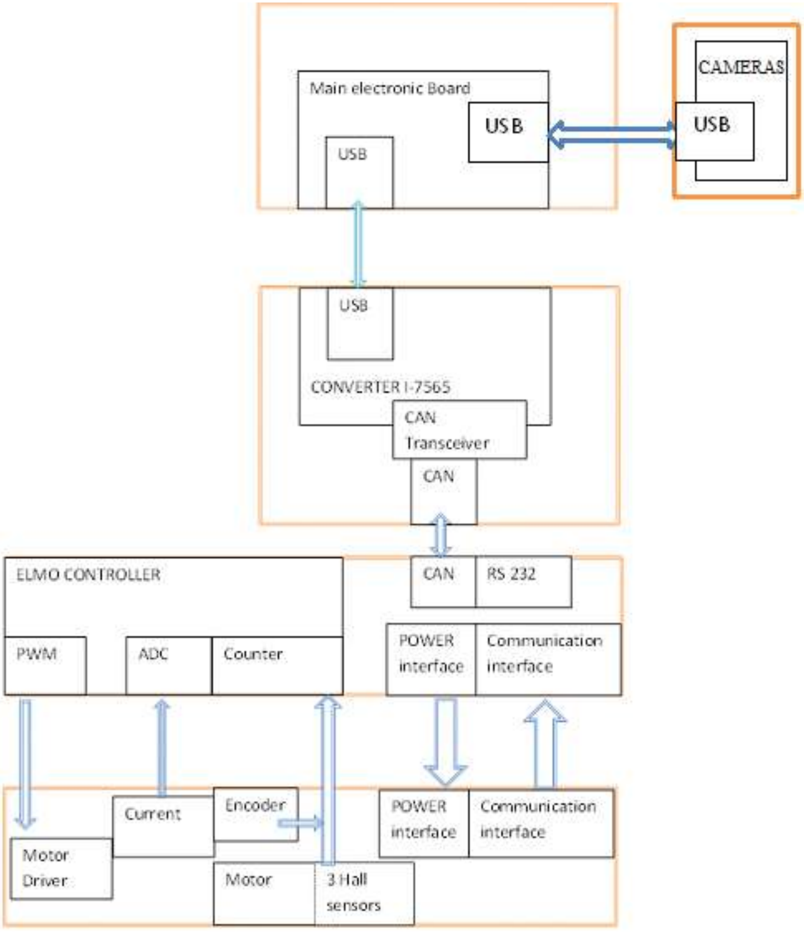


Figure 2-8. The interface of Archie (adapted **(Regenstein & Dillmann, 2003)**)

ELMO controllers are connected into CAN bus through transceiver in the diagram presented in the figure. CAN transceiver that takes the data from the PC transmits into bus and from the bus the controllers will have access.

2.4.2 Software Utility I-7565

Following connection of I-7565 to PC, utility tool software is installed. This software configures the modes of operation, and it also enables testing of CAN bus, to see the module functioning (ICP Das (i-7565 Manual), 2007). Below, at the following figure is given the configuration window of I-7565 Utility software, where conditions of communication of device in CAN network are determined (Fig 2-9) (ICP Das (i-7565 Manual), 2007).

Figure 2-9 Software Utility I-7565 window, (ICP Das (i-7565 Manual), 2007)

2.5 Connectors

Interface between devices that are constituting parts of the robot has a great importance.

The new interface and an advanced one require new device that has relevant ports to be connected. For the Interface between the robot and computer, a USB cable of type A to type B (2.0) that connects the PC and biped robot through CAN converter has been provided. USB cable on one side has type A USB, plugs into PC, whereas on the other side of the cable there is a type B USB plugs into I 7565 device.
USB (the universal serial bus) cables can be up to 5 meters long of full speed. But, there may be up to 30 meters away from host when there is an interface with hubs device.
Cable consists of 4 wires, of two wires for power (5 volts and ground) and twisted pair of wires to carry the data.

Type A plugs face upstream and it is connected on hosts (PC-Personal Computer or Central Controller) and hubs. Type B is connected downstream and is always interfaced with peripheral devices. Connection of computer with CAN converter through a USB 2.0 cable enables communication of Computer with Archie in a speed of 480 Mbps (Technical Information-Diffen, 2015). USB connectors are also of different kinds, most of them separated by type A and B. Type *A* plugs at couple of type *A* socket are built into computers or hubs.

USB cable type A to type B (2.0), on one side has the type A USB plugs in PC and on the other side of the cable there is a type B USB plugging in I 7565 device. (Sourabh, 2014**)**

In the event of a new version of the Archie, with equipping the robot with devices from the newest products, a complete upgrade of the interface must be taken into consideration. There is a new version of USB, such as USB3.0 and USB 3.1. USB 3.0 offers transfer rates of 4.8 Gbps - 10 times faster than USB 2.0. In 2014 USB 3.1(This USB 3.1 used by cameras) has also been provided to the market, thus increasing the transfer rates to 10 Gbps (Gigabytes per second), but is limited in compatibility with past versions. Another advantage is C-type connector that plugs in without regard to orientation, and the capacity to power any type of device (Technical Information-Diffen, 2015). Power consumption is up to 500 mA for USB 2.0, while USB 3.0 provides up to 900 mA. Bandwidth in USB 2.0 uses only one way to transmit data while USB 3.0 transmits data in two ways, taking and giving.

2.6 Summary

At this chapter the system of the Archie interface was described. In our choice to equip the upper part with a vision sensor, a great role is played by the existing interface. Thus the explanation for the interface includes the entire robot, focusing on the upper part of interface. It has been further elaborated functioning of interface with CAN through the communication of the robot. But the explanation for CAN as the main 'highway' of the upper part is connected to the lower part through the main controller is provided, and our concentration is to explain interface of every device that builds body of the robot, including the interface of vision sensor. It is important to note the features of CAN, that it can withstand this number of increasing the number from 12 to 26 actuators with their controllers. Without reducing the performance of communication of the devices with each other, it is conducted through interface, thus technical and software compatibility had to be taken in consideration.

Studies on the system of robot interface are an important part to have information system for good performance during the realization of robot movements. The most important parts of biped robot interface have been described in detail here, with all of key features and specifics.

3 Vision system architecture

"Have no fear of perfection, you'll never reach it"
Salvador Dali

3.1 Introduction

This section describes electrical design, and the electrical connection scheme between the ELMO controllers and the Brushless DC motors including the camera with the PC and with controllers and actuators. Explanations in block diagrams are provided in general manner. It also describes camera in relation to actuators and control. In order to explain the utilization of space in the robot, the hooked up view is illustrated (assembly) of electrical conductors and controllers, actuators. Moreover it provides, attributes, block diagram of the functions and principles of the processing of images. Furthermore it describes the hardware and software structure, forming the interface, and information system with other devices to the robot. It will also be discussed about the hardware part, proposals, and the general outlining on the system of information with particular emphasis on the vision part. It also provides the general bases of visual sensory system for Archie. Furthermore it will also be widely spoken about the entire information system of the robot, in relation to the visual system of robot.

3.2 Vision sensor

For the robot to be orientated in the environment where it operates through cameras, there must be a response following the processing of images captured from the environment, and this processing is enabled by use of adequate hardware. An image captured from the environment where the robot operates is information extracted from the gained image. Human body has a huge number of nerve networks to follow signals to the centre where they are processed, that is the brain, and they are parallel processing signals by giving the response from received images (Society for Neuroscience, 2008). Archie's visual perception system must enable movement in certain trajectory, while the number of video images captured can be up to 30 frames per second, as the robot doesn't have high speed of movement. However, considering that humanoid robots have at least 2 cameras, it is understandable that robot's visual sensors and perception should be on parallel platform. While with the advancement computations such as face recognition, etc. the number of calculations it understands is also added with the processing power. Thus, with the increasing number of sensors, a special subsystem must be organized for the part of the visual system with a cluster of microprocessors. Counting is done parallel controlled by a main board responsible for visual system linked with the main board that is responsible for all subsystems. At this moment high level can be used where the main computation PC is.

Image sensors receive all the data from external environment. Data is converted into electrical signals; it is digitized taking binary values. Following the data processing, the part of decision making is in order, determined on the basis of the defined criteria, and through certain algorithms, the other part is acting, this action in form of instructions are put in action by actuators. Electronic board has been chosen with the possibilities of interface with all digital cameras through Universal Serial Bus, as majority of electronic boards have the Fire Wire and USB ports integrated.

Selection of camera with the option of USB seems to be appropriate. However, USB and Fire Wire are used for digital videos of lower resolution. In advanced robots where digital videos are produced with high resolution, visual sensor systems are used including; image digitizer, electronic camera and host computer (Bouchard, 2011-2016). A much more powerful system is needed for processing images, and those having high speed of signal flow, capturing a high number of images within a second and the use of high number of algorithms. In this electronic board, a powerful graphic card is required for the collection of images and digital data in graphic formats, known as VGA, SVGA, and XGA. In fact all today's electronic boards have that opportunity.

The electronic board will be mounted in the front part of Archie in the height of 90 cm; the total mass may be approximately 400 gr. This mass is fixed to aluminium sheet that is on the thorax of the robot. In this part of the body of the robot, other electric boards can be placed as well in parallel, they can be added with the enhancement of the robot, increasing the number of other sensors, and making more powerful the part of visual system sensor (as we have emphasized above). PC as a host computer, and the electronic board, believed to be integrated in robot, and must be equipped with PCI - Peripheral Component Interconnect for interface image digitizer and other external devices.

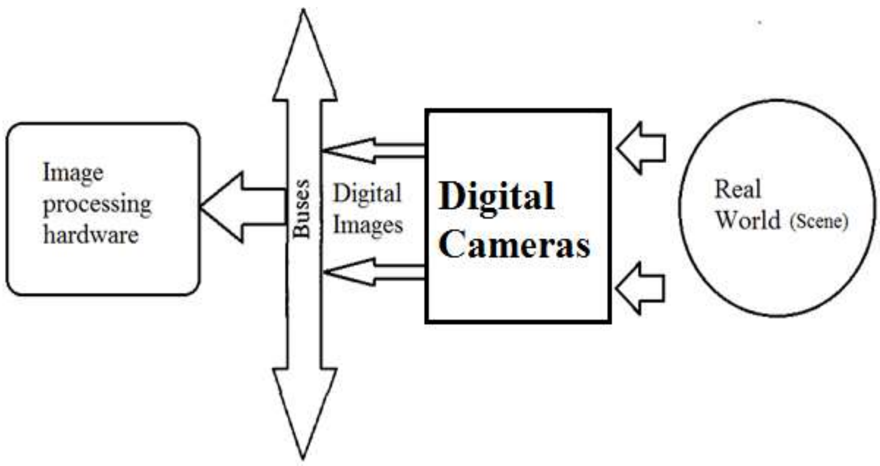


Figure 3-1. Block diagram of digital cameras

Using image digitizer becomes necessary at other electronic cameras CCD. While for our robot we have chosen CMOS cameras with the possibility of connection of USB 2.0.

It was decided to choose this type for some reasons;

- CMOS cameras in general are lighter, and with simpler electronic part.
- In general are found in lower price
- And attributes give enough support for goals in equipping the robot with a visual system, etc.
- Digital CMOS cameras with USB interface after digitalized image processing send the image processing to the hardware (main electronic board). Interface between camera and image processing hardware has been given briefly as an overview in Fig 3-1. Block diagram shows in general the function.

Camera possesses all the required attributes as elaborated above; transfers data in USB 2.0 format, isochronous transfer and Connector USB Mini-B thus enabling a simple interface with the brain of the robot that is the main board, then USB drivers are Compatible with USB. It must be mentioned that all the values of information are taken from specifications, produced by LEOPARD IMAGING INC. (LI-USB30-V024STEREO), (Camera, 2015).

Based on the condition of dynamics of the robot, the camera not only meets the conditions of an easier interface with current electrical design at Archie but it has small size, namely L: 80 mm, W: 15 mm, H: 17 mm meaning that we enough space has been saved in the position of the head (Camera, 2015). Then, except for small dimensions, it has low mass, and that is very important, taking into account the fact that they are in the upper part of the body. Every enhancement in increase of the speed of the robot forces harming of the dynamic stability. Mass of the robot is mainly focused in the part of the hips, and with the increase of mass in this part, the stability to a certain degree is increased in proportion with increase of the power of actuators in the lower part. Our image sensor is compatible with LINUX operating system, knowing that the program of biped robot programming is in C++, LINUX Operating system. Camera used interface USB 3.0 (Fig 3-2). Camera module of high and low quality image with high sensitivity, equipped with CMOS sensor (Camera, 2015).

For every visual system of the robot, transfer speed of frames per second is also important. Speed of the Archie during his movement is approximately 0.07 km/h., and the robot has not yet been enabled to raise his foot higher than 7 mm over the floor, theoretically it maintains stability by raising the foot on the floor up to 12 mm. Thus it is understood that the robot at every software implementation of algorithms in the *Visual Perception System of Robots* must be take into consideration only in the even surface.

Figure 3-2 USB 3.0 Stereo Camera (Camera, 2015)

Transfer speed of the camera is sufficient. The part of obtaining the quality of images is of a high quality, because the video resolution 640 x 480, with frame rate 60 fps, while the size of pixel size; H:6.0 um, V: 6.0 um, image sensor resolution is, H-horizontal 752, V-vertical 480. As the image sensor is CMOS, it shows the little mass of camera, while the part of electronic circuit is simpler in printed circuit board. Camera has the little power consumption of approximately 270 mA at 5 VDC and supply voltage USB 3.0 +5 VDC power source. This is an important fact to note that the robot functions with battery supply in a longer duration.

In the table (Tab.3-1) the camera features are presented as below.

Table 3-1. The features of cameras (Camera, 2015)

Default Lens Specification	**Key Features**
Model: HK-8055-J3	USB 3.0 Super Speed support
Image format:1/3	RAW data output without compression
Focal length: 2.35	UVC compliance
Aperture, F/#: 2,5	USB 2.0 backwards compatible
FOV (D/H/V):115°/90°/60°	Dual Camera
Mount:M8xP0.5-6g	Provide customized services
Built in IR cut filter	USB+5VDC powered device
Compact size:	80 mmx15mm

3.3 The hardware architecture

The low levels of control system of Archie are the actuators with Elmo controllers and image sensor. High level of control includes PC, where the calculations are made, commands are distributed in direction of actuators of the robot, and the information is gathered related to positions of the actuators and their status as part of their feedback loop. It is conducted through USB interfacing PC. The more sensors and other equipment we add to the robot, the more the need increases for the raise of the medium level of control. Hence, the low and the high level of control exist, but the medium level needs to be added.

All the actuators and controllers of the whole body are connected into one main controller for calculations, then another controller responsible for the visual part and other sensors.

In the hierarchy of control and data processing, system failure detection, calculating the location of the supporting polygon, energy and multi-task management, image processing, obstacle detection, calculations of the wanted positions of actuators while walking are made in PC. A simple case of control through a system of vision is presented in Fig 3-3 and Fig 3-.4.

The system consists of cameras and a motor, connected with electronic board. Electronic board makes the processing of images taken from image sensors, according to a certain algorithm, e.g. face recognition, or obstacle detection (Fig. 3-5). Following the calculations and the communication according to block diagram, the motor receives the information from the camera into PC and following a series of processing the decision is made for the wished angle movement of the motor shaft. The flow diagram (Fig.3-3), explains the control system and communication between the cameras and their electronic board, ELMO controller, Encoder and Electronic board.

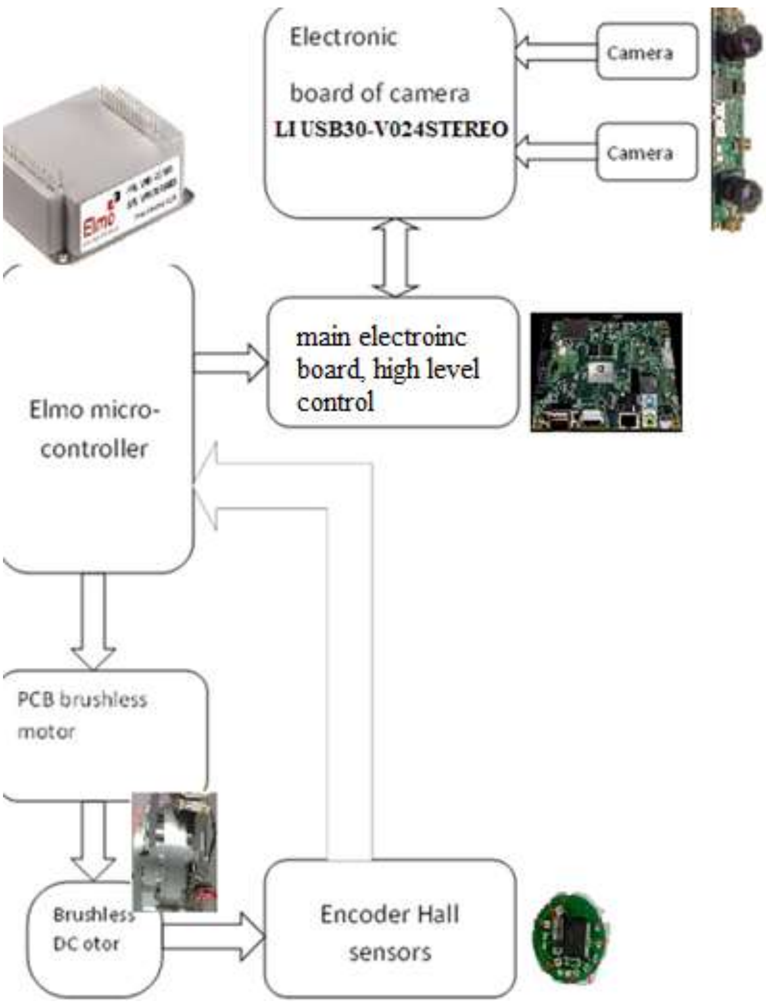


Figure 3-3. Block diagram of control

In Archie design in general, some characteristics have been taken into account so that the robot may have an autonomous movement similar to humans. Some of the characteristics are; to have the human shape and the body mass of an adult, with sufficient degree of freedom. In the current stage of design, the upper body has been constructed, including; head, neck, shoulder arms, and thorax, and visual system.

Visual system contains; main central unit for processing, visual sensor -CMOS with high performance for environment recognition, motion planning, map planning, self-localization, and dynamic trajectory generation. The power of the existing actuators of biped robot based on theoretical and practical conclusions must be sufficient to walk and stand. While the actuators of the upper part must be able to enable the movement of hands, and to help walking of Archie, by moving hands opposite to the movement of legs. The upper part of the robot is not designed to take things or to carry out any work by its hands, or to perform actions such as bending; sitting. A part of the vision must be able that in the trajectory in length and speed mentioned above, to detect obstacles beforehand, and to know a certain object, without harming dynamic stability. The part of vision must be calculated with at least 6 cm distance from the feet of the robot, up to 3 meters.

The other chapters of this project will concentrate on the design of the neck, head and simulations related to control and stability, etc.

3.4 The software architecture

The biped robot uses Linux OS (operating system), and C++ software with the aim to develop the platform and dynamic walking. From electronic board that is the main decision making system, where information is collected for the whole condition of the system, calculations are made and decisions are taken by following to all the equipment; actuators and sensors (actuator encoder values from Hall and image sensors) including sensors that must be integrated in the body of the robot (inclinometers, force sensors etc.). In central electronic board arise main decision system, there C++ is implemented and runs under LINUX operative system. Software architecture is described with block diagram, in Fig. 3-4 and control through vision sensor is described in Fig.3-5.

The more sensors, in future, and actuators of different types are added to Archie, the information system becomes more complex. It makes a data network communication more sophisticated, also the complexity increases in the software and hardware part. Thus the system requires an organization of communication in a more advanced control system, and powerful computer for processing the data.

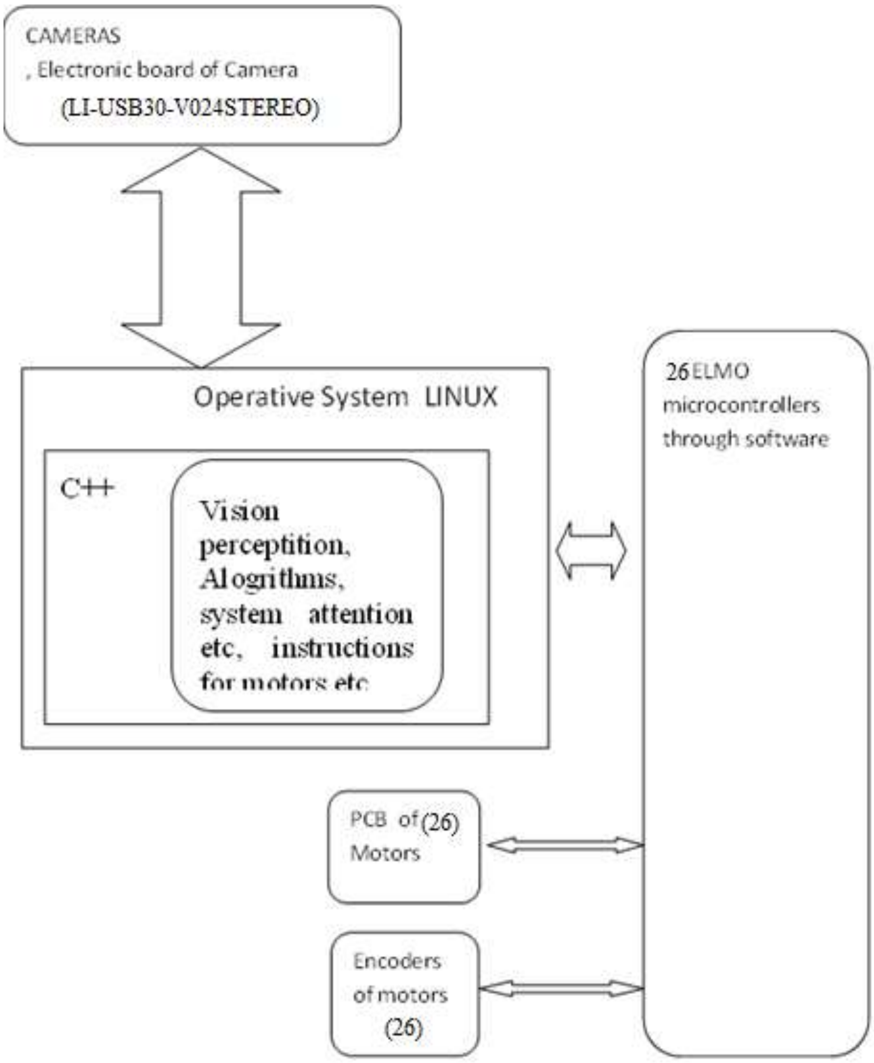


Figure 3-4. Software structure and control through visual system

Data processing and decision making is executed in main unit control - PC. Below are presented the vision sensors, data taken, basic processes carried out within the computer, such as; image catch, image process, mapping, movement control (Fig 3-5), and visual perception for sending information and taking decisions for position of motor's shaft (Xie, 2002). Structure of the visual system, after the completion, with the part of upper body including head and the lower part of the robot

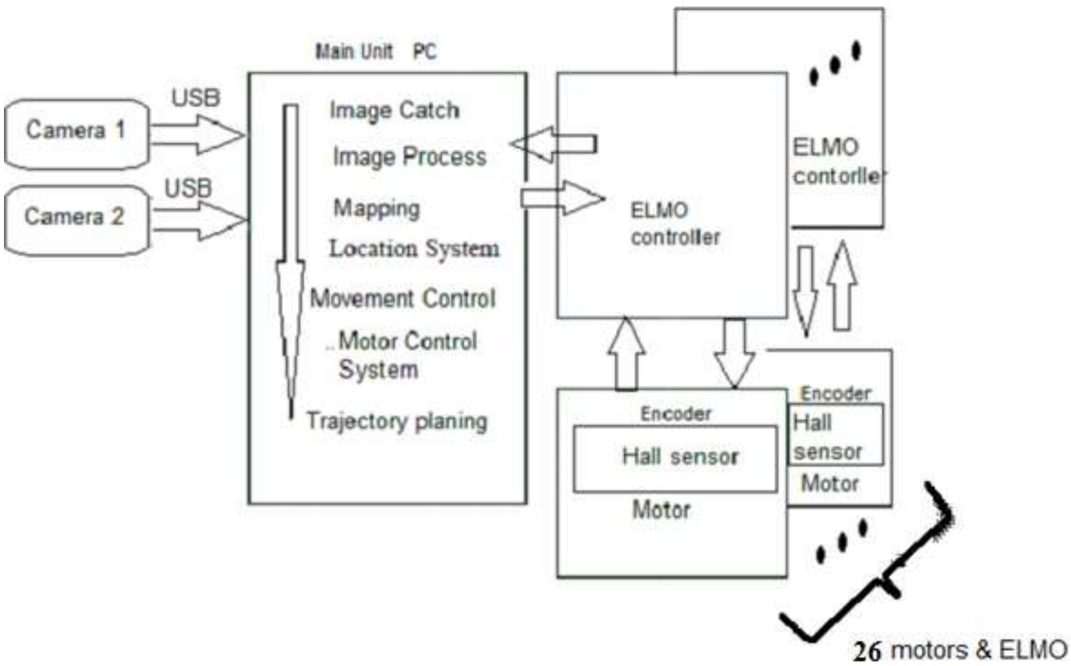


Figure 3—5. Structure of the visual processing and control (adapted, Xie, 2002).

3.5 Visual Perception

In the output of the visual system, the sensory system has digital images that will be ready for input into visual perception, so that this digital data is further processed for perception, analysing and understanding. Computer graphics is the process of gaining sequences of images from the description of objects of the real scene into virtual scene, while visual perception is the opposite process complementing each other (Xie, 2002). Although input in visual sensor is not known in advance, we do not know what will be before the robot, or to say that it depends on the occasion taken from digital image.

Conclusions made by the shape and geometric attributes of the objects in the scene are followed by the process of decision making (Xie, 2002).

With this description, "knowledge" is acquired on the objects in the scene. In fact for visual perception, different mathematical and theoretical studies building certain models and algorithms, afterwards in programing language, to process this digital data of images. Following completion of processes presented in generic block diagram form in Fig. 3-6 below (Xie, 2002), decisions are made related to images received by the image sensors. The simplest example is identification of an obstacle and perception of the object located in front of the robot as an obstacle that must be overcome or jumped over.

With the term scene we refer to the whole area we can see, so the objects located in those dimensions of vision recorded by camera, are in the vicinity of the robot, reflecting into image plan where CMOS sensor is. Block diagram describes the work done by system vision; the hardware and software part from the scene to the moment of decision making and action (Xie, 2002).

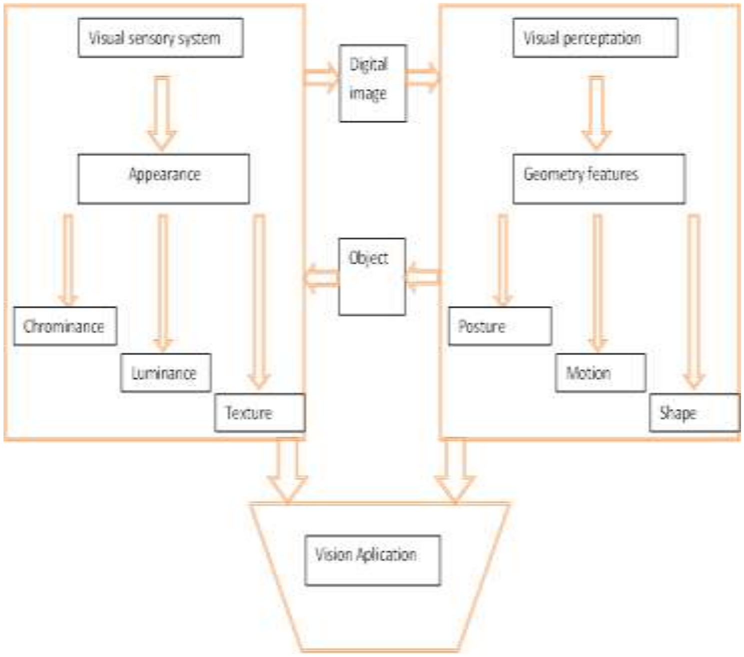


Figure 3—6. Block diagram of the vision system (Xie, 2002)

3.6 Summary

In this chapter the hardware and software architecture of the upper body of Archie were described, as a continuation of the lower body. The design of the upper body will be assembled with actuators in the joints of neck/head and arms. Then the information system was explained on the basis of all the parts of upper body that will communicate to each other. Furthermore, adjustment of movement of actuators, that is conducted through sensors, and the way of communication. The upper part is a continuance of the lower body part, so the explanation was provided as a whole increasing the number of actuators from 12 to 26.

4 Preliminary calculations

"A great deal of my work is just playing with equations and seeing what they give"
Paul A. M. Dirac

4.1 Introduction

This chapter elaborates preliminary calculations that depend on dimensions and design of the low body. Justification has also been provided regarding the decision for robot height to be 126 cm. In this part, provides values of dimensions of the existing low body of the robot, and they have been calculated based on that dimensions of the upper body. Thus, starting from the human body proportions with a height of 180 cm, height of robot, the dimensions of arms and neck have been calculated in relation to the existing part.

Reasons have also been provided as to why these robot dimensions have been designed, giving the sketches of the design as preliminary calculations. A brief description has been given regarding the history of Archie's progress and changes in dimensions of the robot, thus its design has been changed. Reasons have been given regarding selection of the number of degrees of freedom for the head and arm design constituting the upper body. At the beginning, the neck has been designed with 3 DoF, and then with 2 DoF, comparing the performance, price and simplicity of the design.

Design simplicity includes the number of parts constructing the robot, and the parts not to have small dimensions, which are more difficult to be cut, and to be assembled into the robot.

4.2 A brief history of robot

Like the human view robot is associated with requirement for it to acquire the skills of performing human movements. This means that robot design must meet the kinematics and dynamic requirements and should maintain stability. At this chapter more insights are provided as regards to dimensions of the teen-sized Archie. Considering that the robot is built of links connected to each other through actuators, then are put in motion through them.

The history of the design was briefly given presenting its dimensions (for example length of lower limbs was 66.3 cm, whereas in 2014 it grew up to length of 77 cm). Dimensions of the links of the upper body were given, then distribution of the mass in the links build the body of the robot providing it through tables. Dimensions for the upper body have been taken from the existing lower body part of the robot, as well as comparing those dimensions with the human body length of 180 cm.

The values have been expressed in percentage and then expressed in relation to the length of Archie. From the dimensions of the biped robot called Archie, a project launched in 2004 up to 2011 were presented in the Tab.4-1 below (Byagowi, et al., 2010). Comparing development and perfection of the robot, from 2004 until 2014, the changes are obvious to have been made to the dimensions and the design too. Those changes were made in the hips and on the foot and in ankle. The robot has been added a motor in ankles, in 2014, increasing the mass at the bottom of the legs and length of lower limbs of the robot from 66.3 to 77cm (77cm -66.3 cm = 10.7cm). With the increase of the length of the lower body, the length of the upper body changes too.

However, changing the dimensions of a part, re-dimensioning (redesign) is required for the whole body of the robot. Values of the table (Tab.4-1) taken from the design of the paper from 2010/11 (Byagowi, et al., 2010). The table shows the values of longitudes before 2014, at lower limbs and upper limbs.

Table 4-1. The old design of the robot

Parts of Archie	Length (cm), in 2010	Length (cm), in 2014
Upper body	51 (proposed)	
Low body	66,3	77 (exist)
High robot	117,3	120 (proposed)

Starting point of calculating and the decision for setting the dimensions of the upper part (arms and neck/head) were existing parts of the robot. There are taken into account forces that come into effect during the robot movement and the material affording the load. Lengths of human body have been taken in length of 180 cm, measuring length of arms, neck, head, and proportions of length over the realm of eyes. The lengths also have been expressed in percentage in relation to total length of human body having a height of 180 cm. It is worth mentioning that every human body has its characteristics of height, however, approximate values have been taken. The current height of lower limbs of Archie is 77 cm (before 2014 this height was 66.3 cm). From the height of 77cm, compared to the percentage of lower limbs with human body height (180cm), height of biped robot was found in figures of 135.85, and this value has been approximated with 136 cm.

In the following table the length has been measured over the level of human eyes with length of 180 cm that is 12-13 cm, expressing this length in percentage in relation to the total height is 7.2%. This length (7.2 % is approximately 10 cm from 136cm height of the robot) has been removed from the robot. The section over the level where eyes are fixed, this length would be included in any (more advanced) project to the head of the robot, when more human shape is given to the head of the robot that will include approximately the forehead with the spherical head. Only the length from the feet to cameras has been calculated, including 126 cm as is the height of Archie. Length of all links is measured by motor’s shaft. The table (Tab. 4-2) provides dimensions from calculations.

The robot on the part of the torso is thick 14 cm and the part of the lower limbs is 8cm. Existing part and proposed height for the robot calculated with the comparisons and proportions of human body of the height of 180 cm (Tab.4-2).

The part of the head length over the eyes, from human shape (of the height of 180 cm) is approximately 12-13 cm, in percentage it is 136/180=7.2 %, that is almost equal to length of the neck. Archie's part over the eyes' level has the length of 7, 2 % (10 cm) of the total height (136cm-10 cm=126 cm) of its body.

Table 4-2 Dimensions of Archie from the calculations

	Human (cm)	**Percent**	**Archie low body (existed)** (cm)	Dimensions from the calculations (cm)
Length	180	100		135.85
Body without Head/Neck	147	81.67	110	110,948
Body till eyes	167	92.7	126	126.0381
From eyes above	13	7.22	10, (not consider)	9.81138
Upper body	84.6	47		63,849
Low body	95.40	53	**72**	72,005
Thigh (Upper link)	45.31	25.17	30.5	34.19
Leg (Lower link)	43.0	23.88	25	32.44
Ankle (high first joint)	7.00	3.9	**9.5**	5.28
From foot till ankle			**6**	4
Foot length/width/width in heel	29/10/6	15.5/5.5/3.3	22.33/17/16	21.05/7.54/4.48
Head/Neck (high)	33	18.33	26	24,901
Neck (high)	13	7.2	10	9.78
Head width	17	9.45	14	12.84
Hip width	22.5 (45.7)	12.5 (25.38)	**31.7**	16,981 (34,478)
Shoulders	47.5	26.3	40	35.85
Upper arm	35	19.45	26	26.42
Forearm	27	15	20	20.25
Arm	62	34.45	46	46,800
Hand	19.5	10.8	X	14.67

Given that the electronic boards will mainly be placed on its body (Thorax), there is no need to place something else over the level of eyes, and also the cameras do not have a motor for independent move, because of the construction. In the future projects of a new type of Archie, eye actuators can be placed over the level of eyes in order to make eyes' movement independent.

4.3 Data Sheet 7020 Aluminium

Some features of the material with the robot constructed are presented on table (Tab.4-3) (Aluminium Alloy Data Sheet, 2015.)

Table 4-3. Aluminium alloy mechanical properties and chemical composition

Mechanical Properties;	***Chemical Composition***
Forming- Good, **Machining-Good,**	**EN AW-7020;**
Welding- Not Suitable,	**Density**~2,78 [g/cm3]
Brazing/Soldering- Not Suitable,	**Si-**0.35;
Protective Anodising- Fair,	**Cu-**0.20;
Aesthetic Anodising- Not Suitable,	**Mn-**0.05-0.50;
Temper- T6,	**Mg-**1.0-1.4;
Restrict Min N/mm-270,	**Cr-**0.10-0.35;
Stress Min N/mm-320	**Zn-**4.0-5.0;
	Others (each)- 0.05;
	Others (total)- 0.15;
	Aluminium- Remainder

4.4 AutoCAD Software for Design

Design of the upper part at humanoid robot has been developed using AutoCAD 2015 software. AutoCAD is product commercial software application for 2D and 3D computer-aided design (CAD AutoCAD® design and documentation software. It is software to help precise drawing and is very suitable for designing and in technical point of view (http://www.autodesk.com/).

4.5 Dimensions of the design

Through figures below parts from the design are clarified through discussing their characteristics. There are designed three prototypes of neck/head, and three prototypes of arms. The first prototype of the arm can move the robot hands in all directions by extending on the sides, in front and on the back. Hands like end-effector have a much greater working space, similar to human arm; this is realized through 3 DOF in arms, and 1 DOF in elbow, 1 DOF in wrist for version V1 and V2.

Two prototypes of heads give the human appearance to robot providing sufficient movement of cameras through 3 DOF on the neck. There are illustrated and designed in figures, presented in following parts of chapter 5, 6 and chapter 7 for third prototype.

Currently the robot lacks arms, the head and neck, the values of longitude have been proposed. There exist lower bodies including the part of Torso, in Archie. Back of the robot with a length of 45 cm (link in shape of tube has length 35 cm and diameter 2mm, a connecting joint is 10 cm) consists of a cylindrical pipe, connected with a brushed DC motor, and is the only joint in torso. The back is connected with a moving joint, meaning that torso has 1 DOF (a DC brushed actuator, 600*g* mass). Lower limbs contain 13 DC actuators; from them there are two DC brushed motors that help movement of legs and the third DC brushed actuator in hip position, making the torso move, situated on the bottom of spinal cord.

The back part of the robot consists of cylindrical form, where parallel plates of 2mm thickness are linked and serve as thorax. Existing mass is 14.5 kg, without batteries, with the battery its mass goes over 17 kg. The lower part of the body should take 65 % of the total mass. Total mass of the robot (Low body and Upper body) is approximately 21 kg.

The figure provides the physical appearance of the three prototypes of upper body (Fig. 4-1), which will be discussed in detail in the chapters to follow

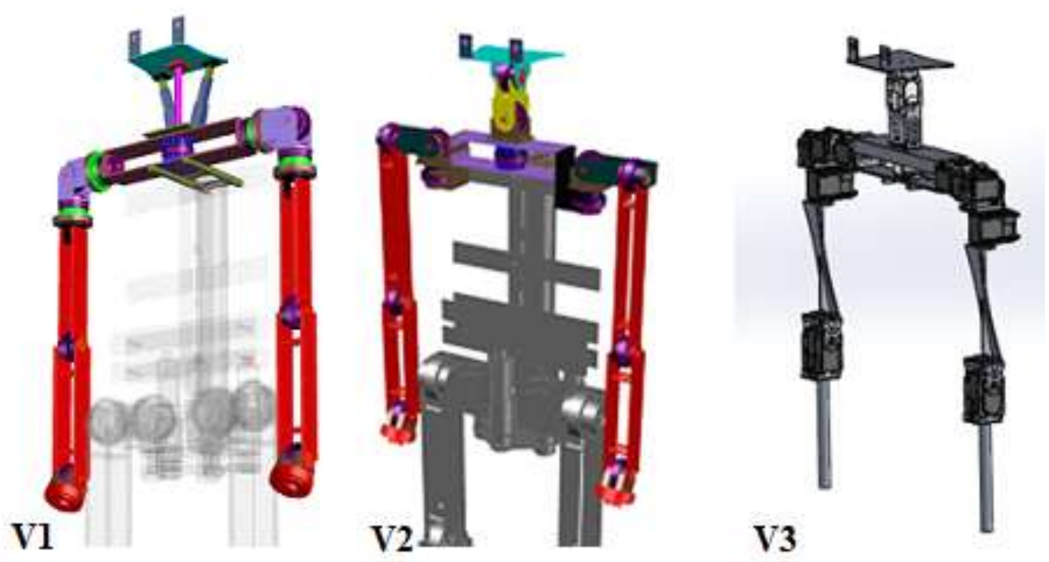


Figure 4-1. Prototypes of Archie (V1, V3 and V3)

4.6 Some design specifics

With the purpose of saving the energy of actuators, attention has been paid to the arm, neck/head design, so that they have as small mass as possible. The part of hands has not been designed. Construction of hands and completing of the head includes the part over the camera, thus, it would make the robot further complete in the future projects. The material used for construction of the upper part of the robot; arms and head/neck, is the same material that has been used for construction of the lower existing body. Any other type of material can be used, but with a condition that material properties be approximately the same with the material used in the lower part.

4.7 Design of Head

The main part of the head will be the zone of the neck, while the part of the head attached to the neck will it be a mobile platform, where cameras are fixed. Of course, the design of the neck should allow the robot, sufficient movement of cameras, and its way orientation of the robot too. With the increase of the actuators to the robot, the number of grades of freedom is added on the head, thus enabling more complex moves of the robot and closer vicinity with the movement.

The first prototype of the neck/head (chapter 5) has combined neck, with two linear actuators and Brushless DC that helps *pan* movement.

The second prototype of the serial neck/head has three brushless DC motors, see chapter 6.

The third prototype has serial neck/head with two Dynamixel motors (chapter 7). The advancement of the design of head means that the head will be on the shape of human head, including the face. The part of the head, where the part of the face, jaws, eyes and forehead are, in Archie robot will not be developed. Cameras chosen for the robot are placed on one plate, so both cameras are fixed on the plate, they cannot move independently of each other. The design of the head of biped robot will include the neck and cameras. Actuators on the neck will help making the necessary movement, for orientation. Types of the neck vary from each other, from the type of motor to be used; in one prototype of the neck two linear actuators were used.

From this, it should be known that the length of the neck is limited by the space available, without exceeding the overall height of the robot (126 cm). Design neck/head of the robot with 3 DOF, are provided through 3 actuators. To maintain the length of the neck in the desired proportions given on the table (Tab.4-2), a motor is added in the middle of the shoulders of the robot to make pan movement of the head. The main part of the head will be the zone of the neck. The part of the head attached to the neck will be a mobile platform, where cameras are fixed (see, chapter 5).

Of course, the design of the neck should allow the robot, sufficient movement, and this way orientation of the robot. In the upper part of the biped robot, the shoulders are designed, proposing three versions called; prototypes V1, V2, and V3. Also for the head of the robot three versions have been proposed, and they will be discussed below

4.8 Clarification

In this work, all the three prototypes have been referred to by abbreviations

- The first prototype is marked by V1
- The second prototype is marked by V2

- The third prototype is marked by V3

Mass of prototypes V1 and V2 is approximately equal; therefore, simulations and mechanical calculations provide the approximate values.
This work also provides the mechanical calculations and values of simulations of V2. For V1 and V2 the same actuators have been proposed, and one interface, electronic, and information-technological components discussed more broadly in Chapter 1 and 2.
For prototype three (V3), Dynamixel actuators have been proposed; Rx-64 for arms and Rx-28 for the neck. In the chapters to follow, elaboration has been provided regarding the design, interface and the mechanical, electrical structure and simulations.

Neck has been divided into three parts for V1 and V2 (Neck 1 – the first link, Neck 2 for the second link constituting the neck). Whereas head has been called the board which is part of a link where cameras are mounted. V3 Neck is made of two links and the board where cameras are installed representing the part that is called head

4.9 Summary

Design of the upper body of Archie is conditioned by the design of the low body. The following points have been taken into consideration while preparing the design;

- Efforts have been made when making the design of the upper body to have it as identical as possible to the low body in order to have a complete robot body as entirety
- At V3 design, efforts have been made to have as low price as possible, and as simple construction as possible

Proposal is hereby made to make changes in the future in the low body to adjust to the upper body of the prototype V3.

5 Design of first prototype

"All things work together..."
Holy Bible - Romans (8:28)

5.1 Introduction

The chapter shows the design of first prototype (V1) then it further includes: neck/head, shoulder and arms. Linear actuators used in the neck have been described, and the most important parts holding the upper body attached to robot's back.

Furthermore it provides the weight of links building the mechanical structure, dimensions, centres of the mass, movable range of joints etc. Figures have been illustrated in order to read values of designed parts and the view. It has been broadly continued with explanations on other features of the design.

5.2 Neck of V1

Linear actuators are electromechanical equipment exchanging rotational movements through special mechanisms into a linear movement with back and forth move of the shaft. Linear actuators are nowadays used at humanoid robots. Their growing use also depends on the shape, different sizes too, from small ones to those that are quite large. There are different types of linear actuators, imitating quite well the human leg muscles, those of the neck and hands. Neck/head of the first prototype is equipped with two linear actuators. Dimensions of actuators have been taken from Linear Actuators L12 from the Company Firgelli Technologies Inc., (Firgelli Technologies', 2012). Any type of linear actuators can be selected with approximate sizes for our design.

The platform cameras of the robot are attached, they move in coordination of linear motor, to orientate the sight of the robot to a specific object. At version 1 (V1), the neck consists of 1 brushless DC motor with revolving shaft, along OZ axis, and two linear actuators.

As two cameras are mounted on one electronic plate, with this the independent move is not possible from each other. Therefore this design makes movement of cameras through the neck of the robot. Movement of linear actuator number 2, moving down - up the platform 1. The platform is orientated depending on the linear movement of actuator shaft (Fig 5-1).

Platform 1 is attached to shaft of actuators through the ball and socket joints link. The platform is also mounted between it and the pillar number 3 that is connected to platform 1, with the ball and socket joints link.

Two actuators (number 2) also pillar (number 3), are attached and fixed to platform number 5. A platform is fixed to the shaft of the actuator 5 that makes rotary movement together with platform 1, making the pan movement.

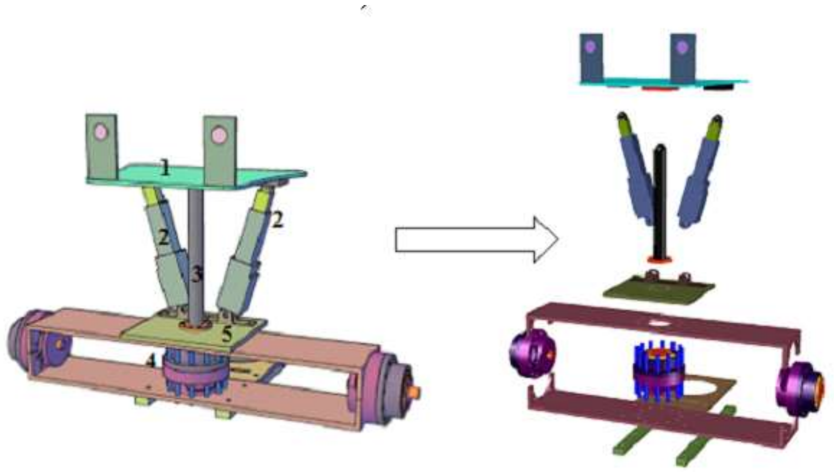


Figure 5-1. The first prototype of the neck

Motor 4 makes movement + /-360. Size of every part (actuators, platforms) is given in Appendix - A.

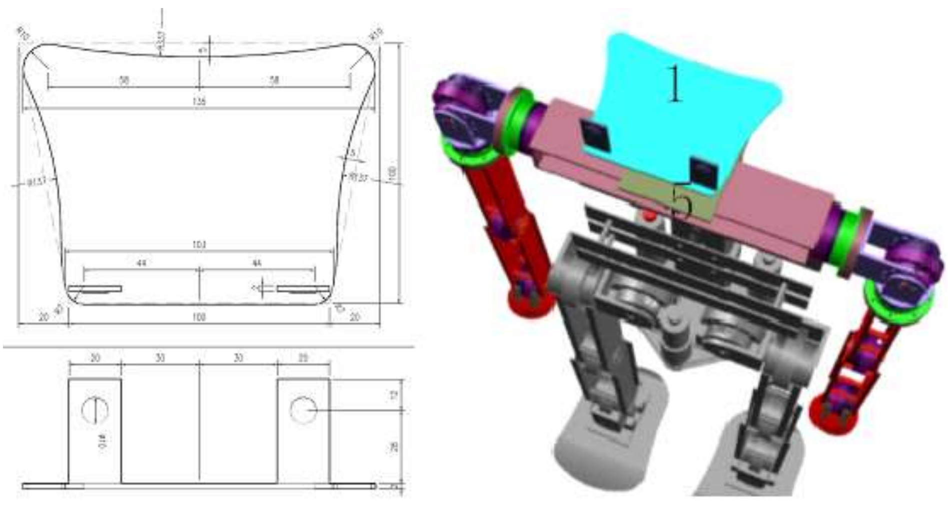


Figure 5-2. View from the top of the robot V1.

Number 1 marks the platform where the plate of cameras is fixed, whereas with plate 5 it rotates motor 4 where linear actuators are fixed (Fig.5-2). The design of the neck is given in figure (Fig.5-3).

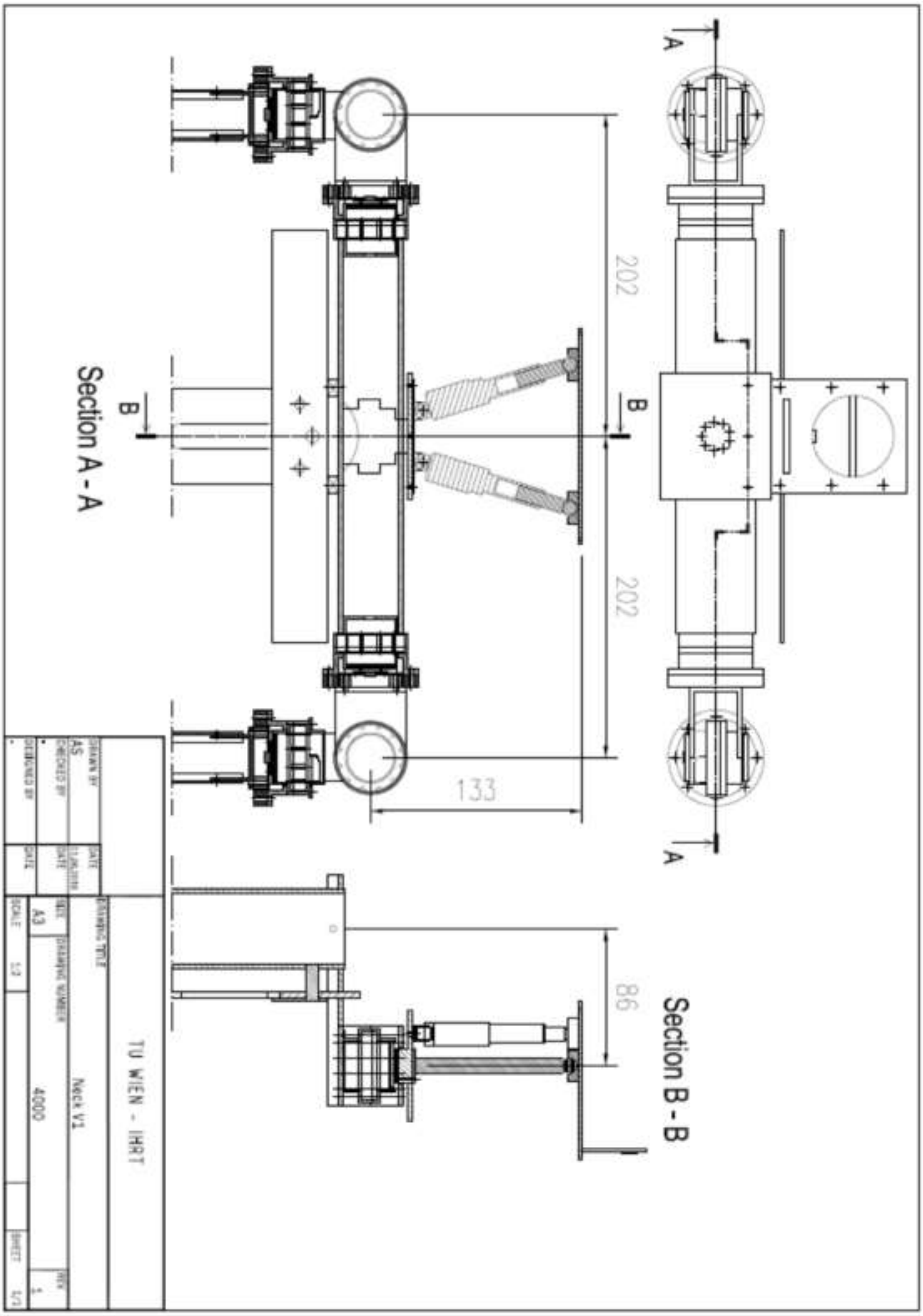


Figure 5-3. The design of Neck V1

5.3 Upper limbs of V1

Human shoulders perform movement, at a higher degree than it has been created at robots. Movement of the shoulders and human arm in combination of other joints, with muscle elasticity make the moves in quite a high level. For the robot, similar to human shoulders, 3 actuators are designed providing 3 DOF at the shoulder of the robot. Human elbow during the movement gives two degrees of freedom - flexion, extension of forearm that it realizes with the upper arm muscles. Whereas pronation and supination movements are carried out by human through forearm muscles, helped by the hinge joint, where two bones meet and during the movement they change their positions (ulna, radius) connected to hinge and put to movement from muscles. In most of the robots, movement of the hand is done by the motors in the wrist, while forearm does not move. Robot has a motor in the elbow making flexion/extension movement of the forearm. Mechanical design of the robot arms and their view in the robot, are given in the figures above, where the rotary joints are given.

The movement of joints is performed along the rotating shaft of motors. All motors are brushless DC (with respective incremental encoders that measure position, velocity) linked with one another through the links, forming a structure of 5 DOF kinematics.

At the elbow, there is a brushless DC motor that makes flexion of the elbow and the same type of motor like in shoulder and wrist. Wrist has a rotating joint with a range of mobility (+ /- 90). Following the joint in the wrist, there is a flange. However calculations have taken into account this part noted as a link. The robot in both arms contains 10 DOF. Both arms are connected through shoulders; two wide brackets contain motor of the neck and sufficient mechanical strength to hold the arms of the robot.

5.3.1 The part holding the shoulders

Below is the design that is part of the first prototype of Archie. The figure presents the design of the holding part. The holder of robot shoulders consists of two parts marked in Fig. 5-4. The position of that part in robot is provided the way it looks from the top view, and is marked by H letter. All consisting parts, design and dimensions are given in Appendix-A.

The holder consists of two parts;

- The plate that enters in the cylindrical backbone of the robot, provided in figure (Fig. 5-4, under a).
- And two joints entering under the plate a) and both of them *a)* and *b)* are put under brackets that hold the arms and the head (Fig.5-5).

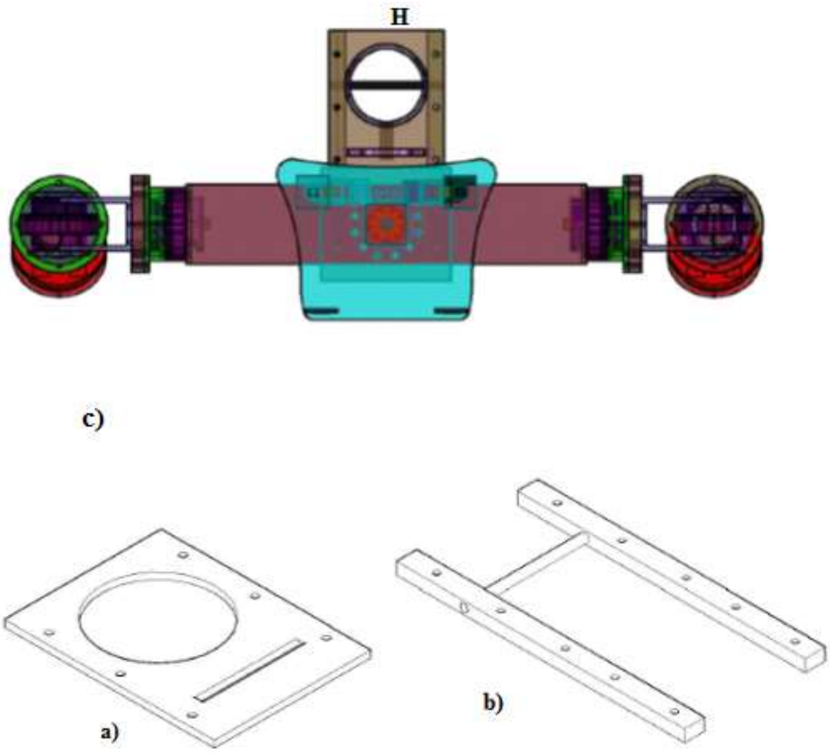


Figure 5-4. View of shoulders

5.4 Shoulder of V1

The shoulder of the robot has been designed and the arm has 3 DOF (degrees of freedom), making sufficient movement for imitation of human arm.

At the part of the shoulder it contains a brushless DC motor number M1 helping the arm to make pitch movement, while motor M2 makes roll moves and M3 motor moves yaw. The motor M3 helps in the pan movement of the hand. While designing the shoulder, the torque was reviewed when the arm is directed to OY shaft, thus activating the M2 motor and by shifting for 90 degrees, at that moment the arm stretches. From here, it has been seen that the entire mass of the arm (upper arm, lower arm and hand), can make pressure on the links between the links where M3 motor is linked. The motor M3 is linked with the socket screw for U-brackets, the mass of one arm in this stretched position of the arm can bring heavy mass at socket screw at the moment of speedy raise. To reduce the risk of robot arm damage, the link was established through bearing, thus mediating the connection between motor with U brackets and M2 motor. Work has been done on the bracket that was marked as M3 for the motor.

The part that contains the bearing is marked with number 1. Part number 1 helps movement of the bearing mediating between M3 motor and the arm part. The figure (Fig 5-5) provides three brushless DC motors, with the number M1, the one that connects and is held by two plates of the shoulders with a thickness of over 3mm, holding 3 motors, so the joint of the neck ensures pan movement of the head

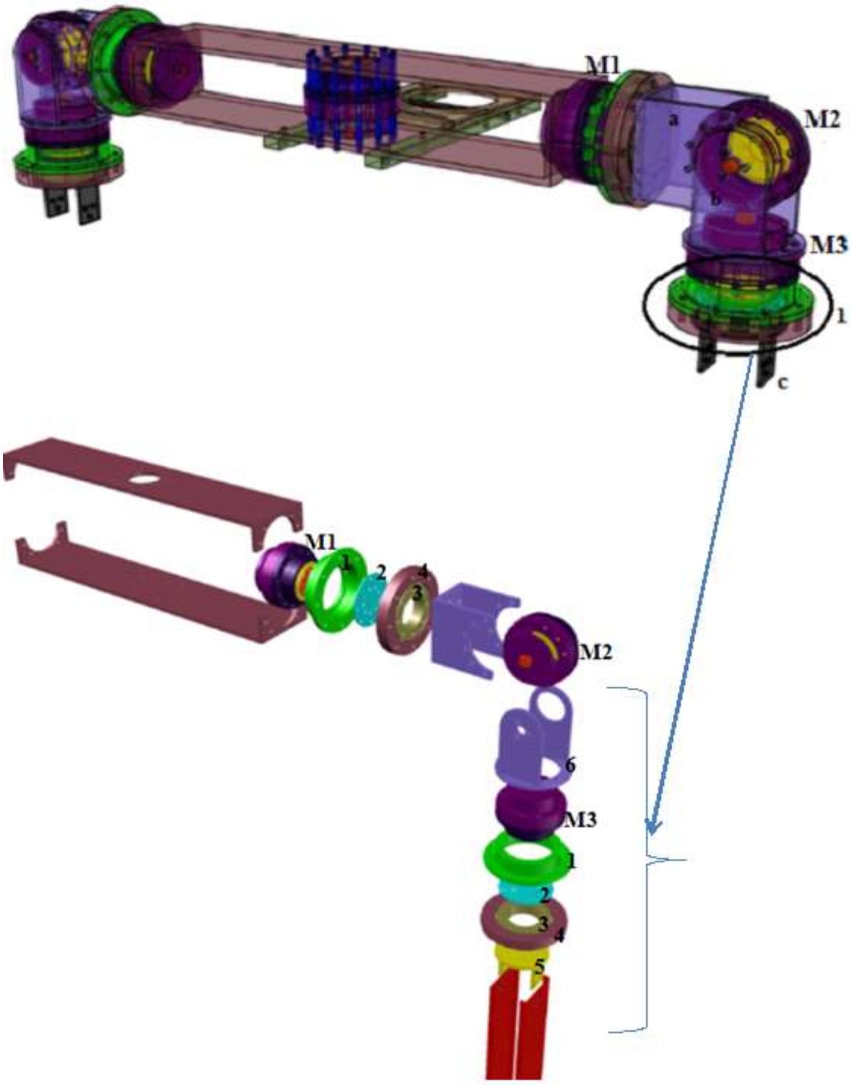


Figure 5-5 Shoulder of Archie V1

With the number M2 is marked the Pitch Shoulder motor, and is limited in movement in direction of the robot body (Fig 5-6).

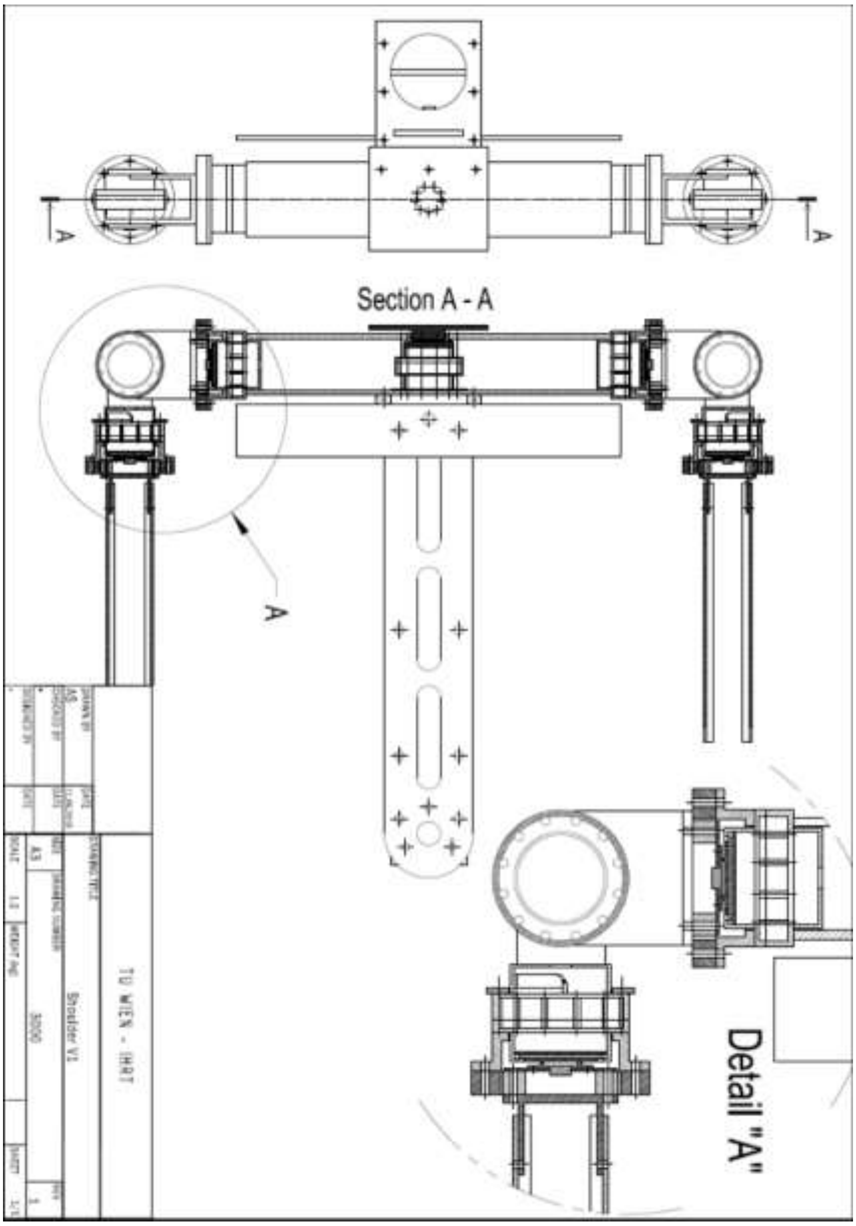


Figure 5-6. The design of Archie's shoulder

5.5 Arm of V1

The below Fig 5-7 presents the view of the link design building the arm of the robot at the part of forearm, arm, and the wrist and the flange. Dimension of the motor and the view are seen in the part of Appendix – A, in a part by numbers it provides all dimensions and the view of every part.

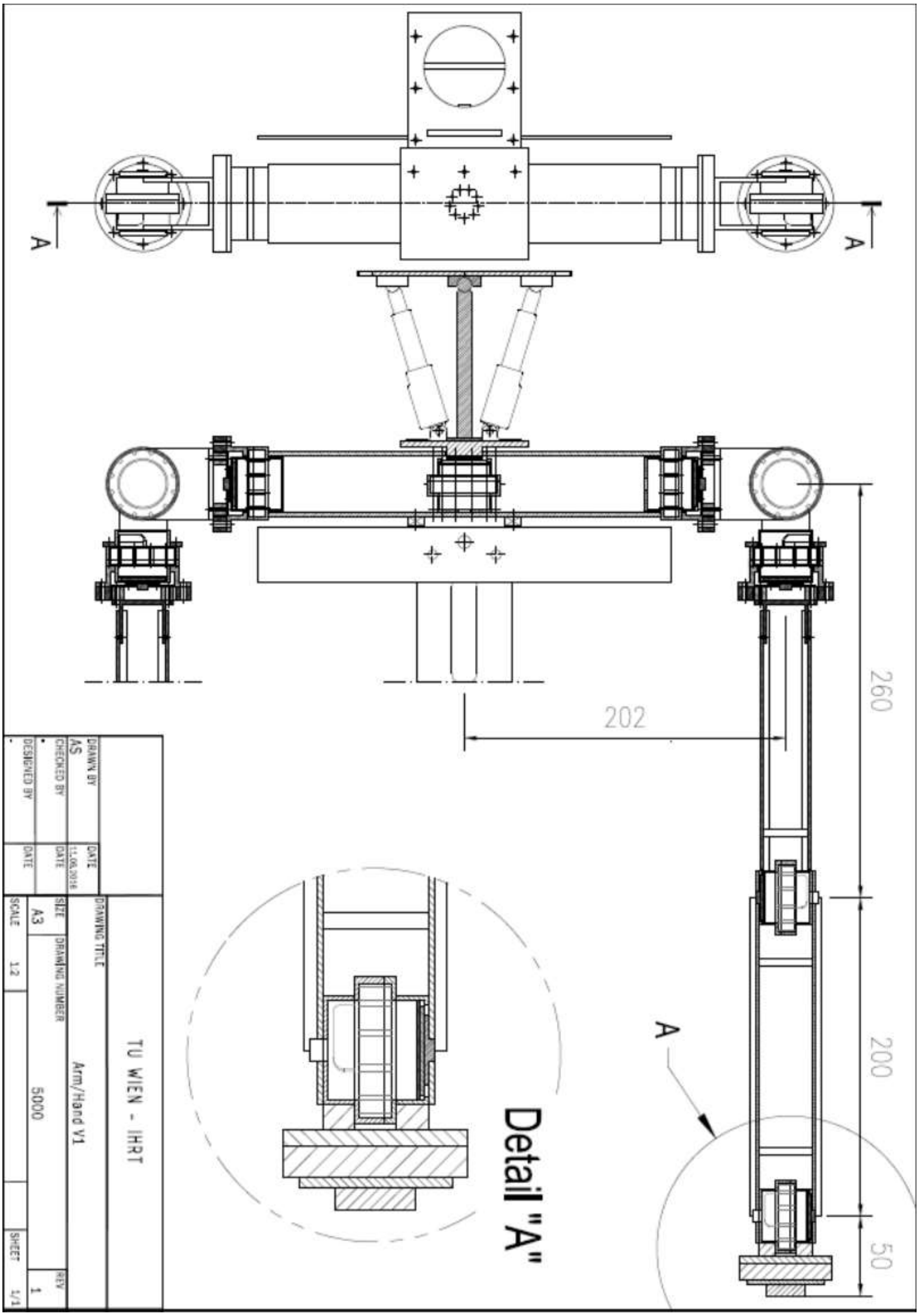


Figure 5-7. View of the part Arm and Hand V1

5.6 DOF Configuration of V1

The number of joints of the robot is 26 DOF (degrees of freedom). The size of the movement angle of motor shaft in the design has sufficient space to generate the desired movements of the robot, (Tab.5-1)

In the first prototype, at the part of the eyes, two actuators are given for linear movement (V1); all other actuators are revolving brushless DC (Fig. 5-8).

It has been proposed that all actuators of the upper part to be the same with those of lower part. Dimensions of actuators of the upper part of the robot are smaller, and their power in compliance with the position and the load that a motor may have.

The mass has been mainly concentrated at the lower part, respectively at the position of hips. The width of the feet and two actuators in the ankles increase stability of the robot. In the elaborations below, the masses of actuators have been considered. Distribution of mass is symmetrical from the sagittal plane; the biggest mass has been concentrated on the hips. To increase the stability of the robot, COG must go down, as close as possible to the floor. Centre of the mass for the whole robot is at the height of about 58. 7 cm (for V1) and 56.76 (for V2) cm from the floor, for both designed prototypes.

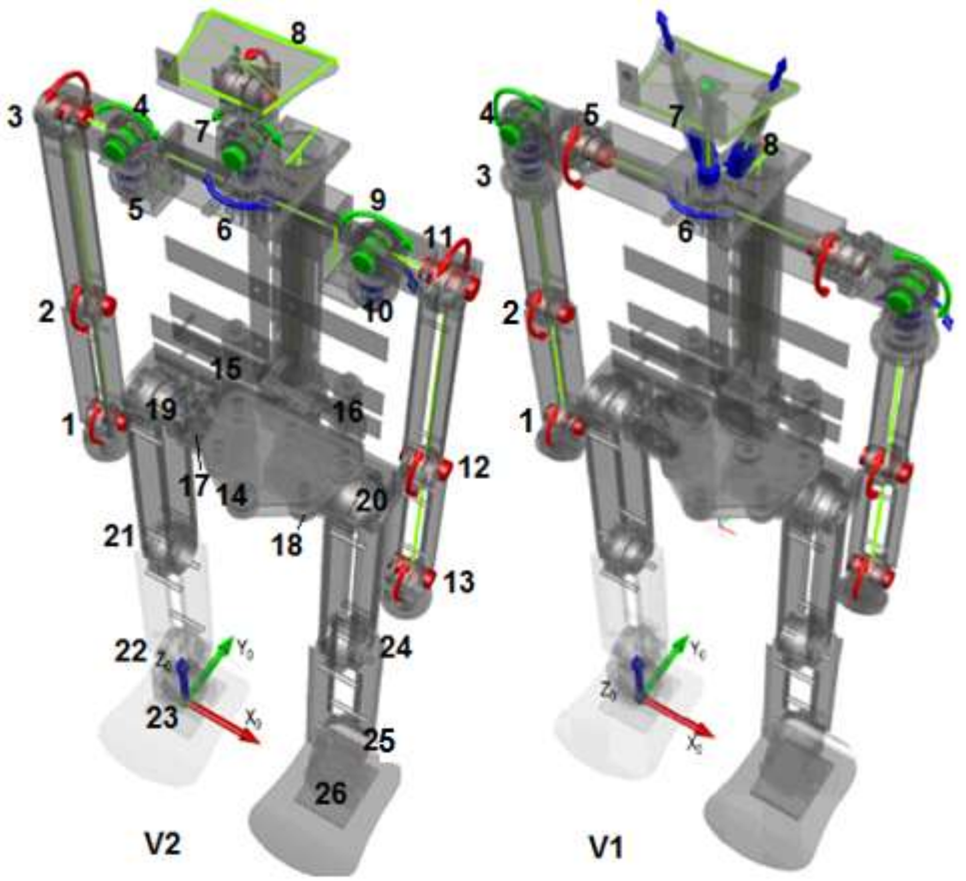


Figure 5-8. Counting of actuators

The movable range of each joint is given in table (Tab. 5-1) and (Fig 5-8).

Table 5-1. Movable range of joints V1

Joints	***Range***	***Joints***	***Range***
M1(θ_1*)*	*+/-90*	*M5(*θ_5*)*	*+/-360*
M2(θ_2*)*	*+/-90*	*M6(*θ_6*)*	*+/-360*
M3(θ_3*)*	*+/-90*	*M7(*θ_7*)*	*+/-4 cm*
M4(θ_4*)*	*+/-180*	*M8(*θ_8*)*	*+/-4 cm*

5.7 Marking of links

The area between two actuators constitutes the distance that represents the link, composing parts of the robot. Actuators link two other links with each other and present the joints. Marking and counting the links starts from the right hand, neck/head, to the left hand (Fig.5-9). The whole part between hips and neck and arms, can be considered a link that represents Torso located between some actuators, where the main electronic board is. The first prototype has a two linear actuators and ten brushless DC motor.

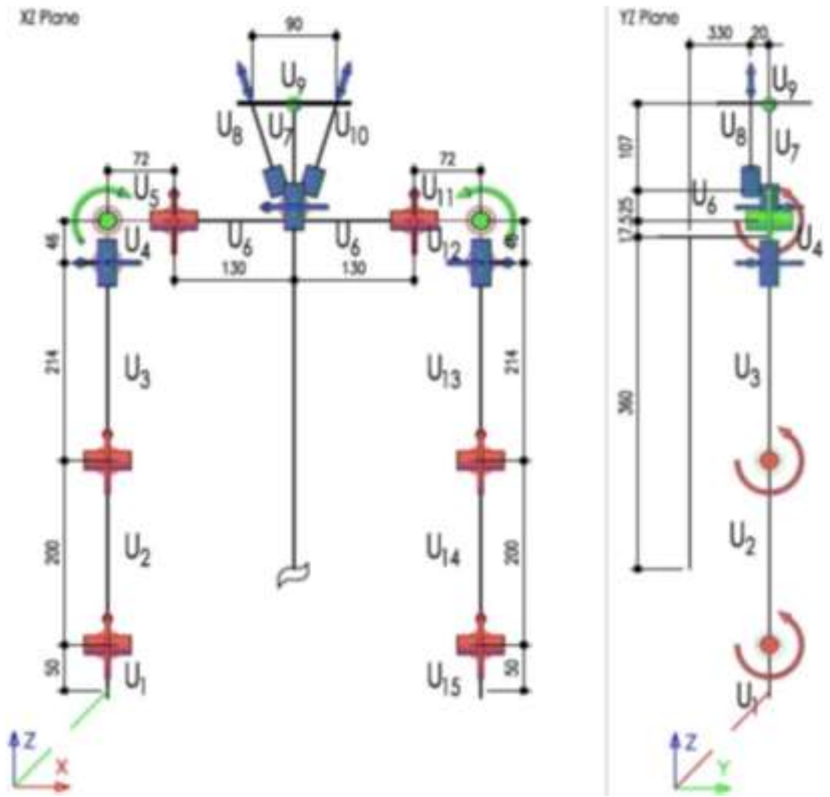


Figure 5-9. Links of the robot

The name has been given with the capital U letter, meaning that U1 to U15 show the links of the upper part of the robot (Tab.5-2). The designed part has 13 actuators; two of them are linear and are in the area of neck/head and move the platform where cameras are, directing the cameras in the desired direction. The link U9 is marked with distance of platforms and cameras are installed on it. This distance (9 cm) represents two points where two rods of linear actuators are attached in the platform, through the joint with the ball and socket joints link.

Table 5-2. Length of links of the robot

Link's name	**Length (mm)**
U1(U15)-hand (fore wrist)	50
U2(U14)-lower arm	200
U3(U13)-upper arm	214
U4(U12)-part of upper arm	46
Length of arm-total	**510**
Shoulder	
U5 [U11]	72
U6	130
U6'	130
Total U6 (U6+U6')	**260**
U5+U11	144
Total shoulder's length	**404**

5.8 Centre of mass

The following table provides centre of the mass for every link, and masses of every link, of the arms and neck/head (Tab.5-3). From values, the values and moments of inertia are given. The table presents the symmetric distribution of the robot mass, in view of sagittal plans of the robot. With the ordering of links on the table, the symmetric distribution of the robot is given. Sagittal plane link U9 divides in halves, separating the mass in two parts of the mass of 88/2 = 44 *g*.

In Fig.5-10, the reference system of coordinates has been given

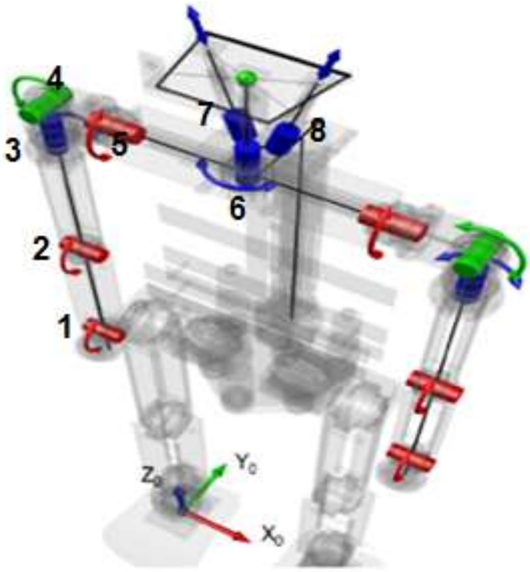


Figure 5-10. The reference system of coordinates

The coordinate system counts the centres of mass of each link of the robot are given Tab (5-3). The following figure (see Appendix A, page 157) provides the exact values gained during the design.

Table 5-3. Mass and the centres of mass of each link

Link Name	***Mass (g)***	***Centre of mass X (mm)***	***Centre of mass Y (mm)***	***Centre of mass Z (mm)***
U1	255	-72	0	615
U2	280	-72	0	740
U3	334	-72	0	1000
U4	198	-72	0	1077
U5	282	-27	0	1100
U6	637	130	15	1097
U7	59	130	10	1130
U8	34	99	20	1176
U9	88	130	0	1230
U10	34	161	20	1176
U11	282	287	0	1100
U12	198	332	0	1077
U13	334	332	0	1000
U14	280	332	0	740
U15	255	332	0	615
Total mass	3550			

5.9 Summary

The design contains the part with the smaller dimensions, which take time when assembling and disassembling the robot. Also cutting and production of small parts is more difficult. The design of the upper body was made as continuation of the low body, in order to be fully identical.

6 Design of second prototype

”Good design is good business”
Thomas Watson Jr.

6.1 Introduction

This chapter outlines the second prototype dimensions, and also discusses the design giving the calculated values of length of links, the mass and centre of mass of links. Designing second prototype, mechanical requirements, simplicity of the design, price, the natural appearance and design to be in accordance with the design of the lower part of the robot have been taken into account.

The neck of the first prototype is of the combined form, the neck of the second prototype is serial with 3 actuators, making rotary movement of the OX, OY, and OZ axis. Actuators have been selected based on the type of existing ones. Every type of motor and harmonic drive that can be taken for robot is followed by the change of design dimensions. In total of V2, robot contains 26 actuators, 13 of them have been designed as a proposal for neck/head, arms, completing the biped robot. The first prototype of the arms has priority to the second prototype of arms, because the design of the second prototype can lift arms on angles of 90 degrees, but only in a narrow angle. The second prototype hands move only forward and in back and forth shakes similar to legs, thus helping the robot to walk (Fig. 6-1).

Versions of the head in fact include the neck and cameras placed on the highest part of the body of robot. Cameras are located in the height of 126 cm. Two versions of the necks have 3 DOF creating sufficient movement of cameras and third version has 2 DOF (degrees of freedom). The difference of neck/head of the first and second prototype stands in two actuators. The first version ones are linear mini actuators. Actuators contain servo drives with a mass of 150g (mass of motor is 50 g), fed with 20 amps, density of material from what they are built allows a peak of 3200 W of power and 1600 W when their work is normalized (www.elmomc.com, 2013).

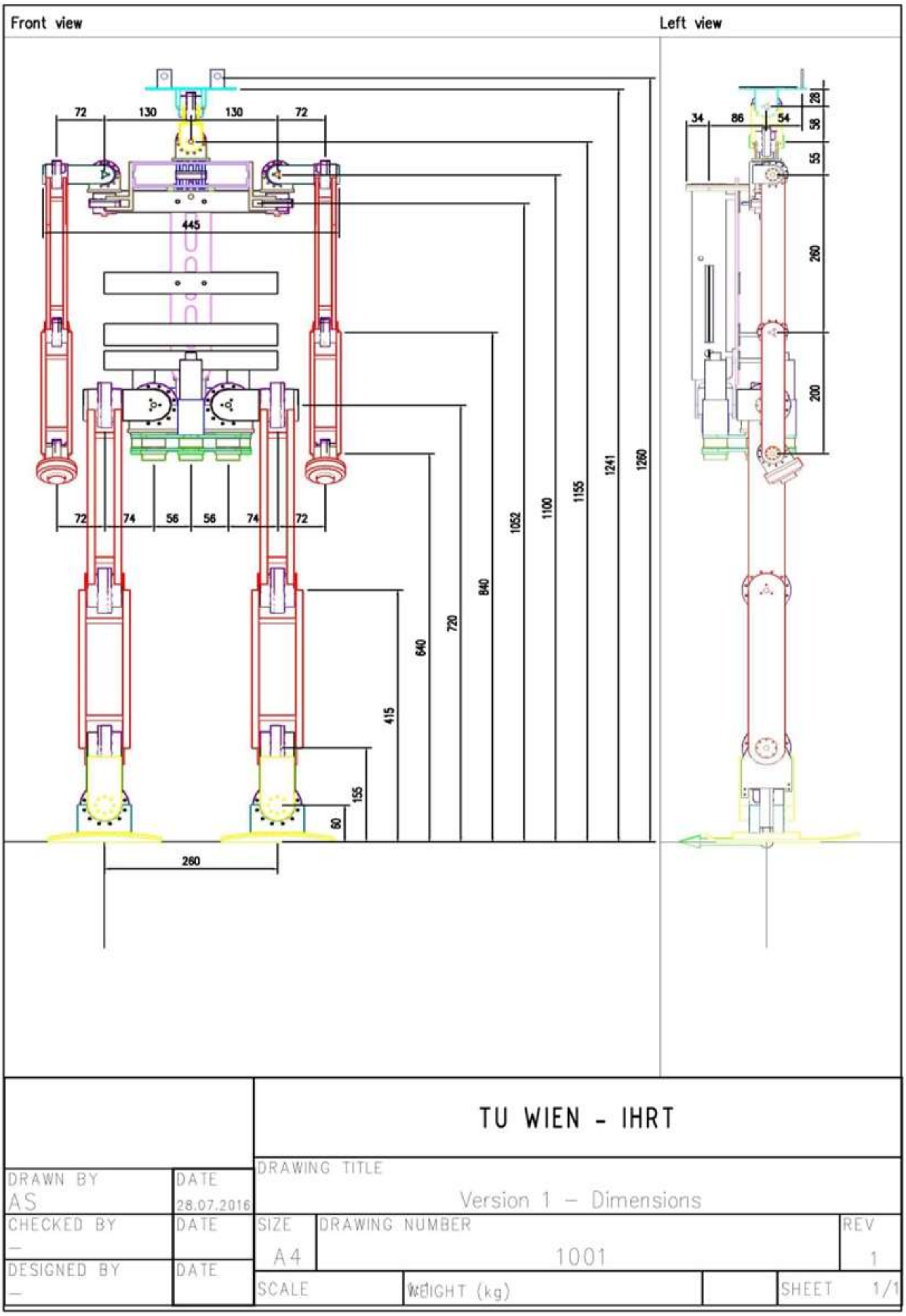


Figure 6-1. The design of the second prototype

6.2 Neck/head of V2

Design of the head contains the part of the neck, whereas the remaining part of the head consists of cameras. Cameras are focused on the mounted platform over the neck so the movement of cameras is carried out through the neck. Distance of cameras has been given by the producer, and the distance from each other is 5 cm getting close to anatomic details as human eyes.

In the second part of the figure (Fig 6-2), it is divided in parts composing the neck. Numbers 1, 2 and 3 have been presented at actuators which make pan, tilt and yaw movement of the plate number 4. Design of robot's eyes does not let the cameras of the robot to make movement independently, because both cameras are attached to the same printed circuit board. Neck contains three actuators providing sufficient movement of cameras.

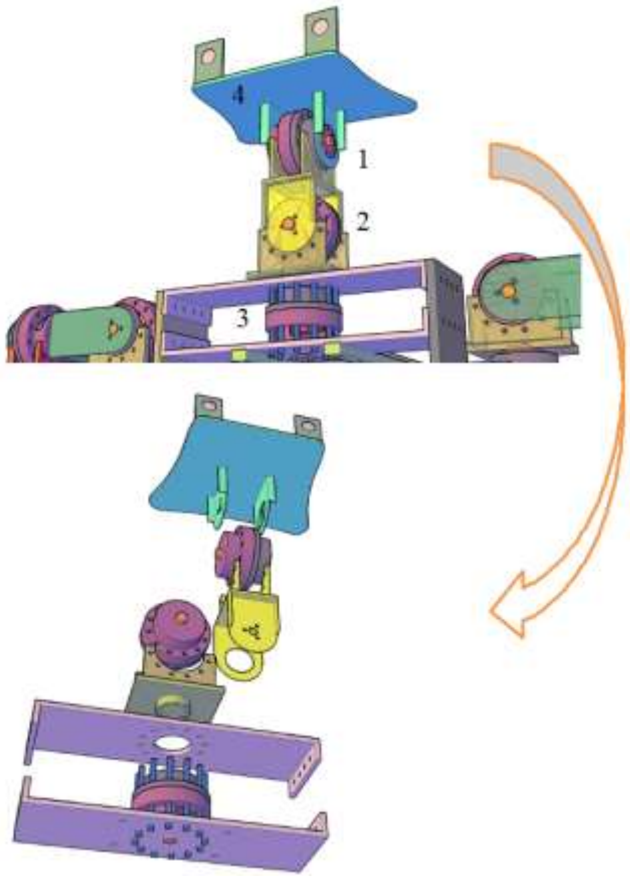


Figure 6-2. The second prototype of Neck

Actuator 3 (Fig 6-2 and Fig 6-3) mounted in the level of arms helps pan movement of the head/neck. Brushless DC motors marked with numbers 1, 2, 3 to make sufficient movement of cameras for orientation of the robot. The movable range of Neck V2: V2; M1 (+/- 60), M 2 (+/- 45), and M 3 (+/- 180).

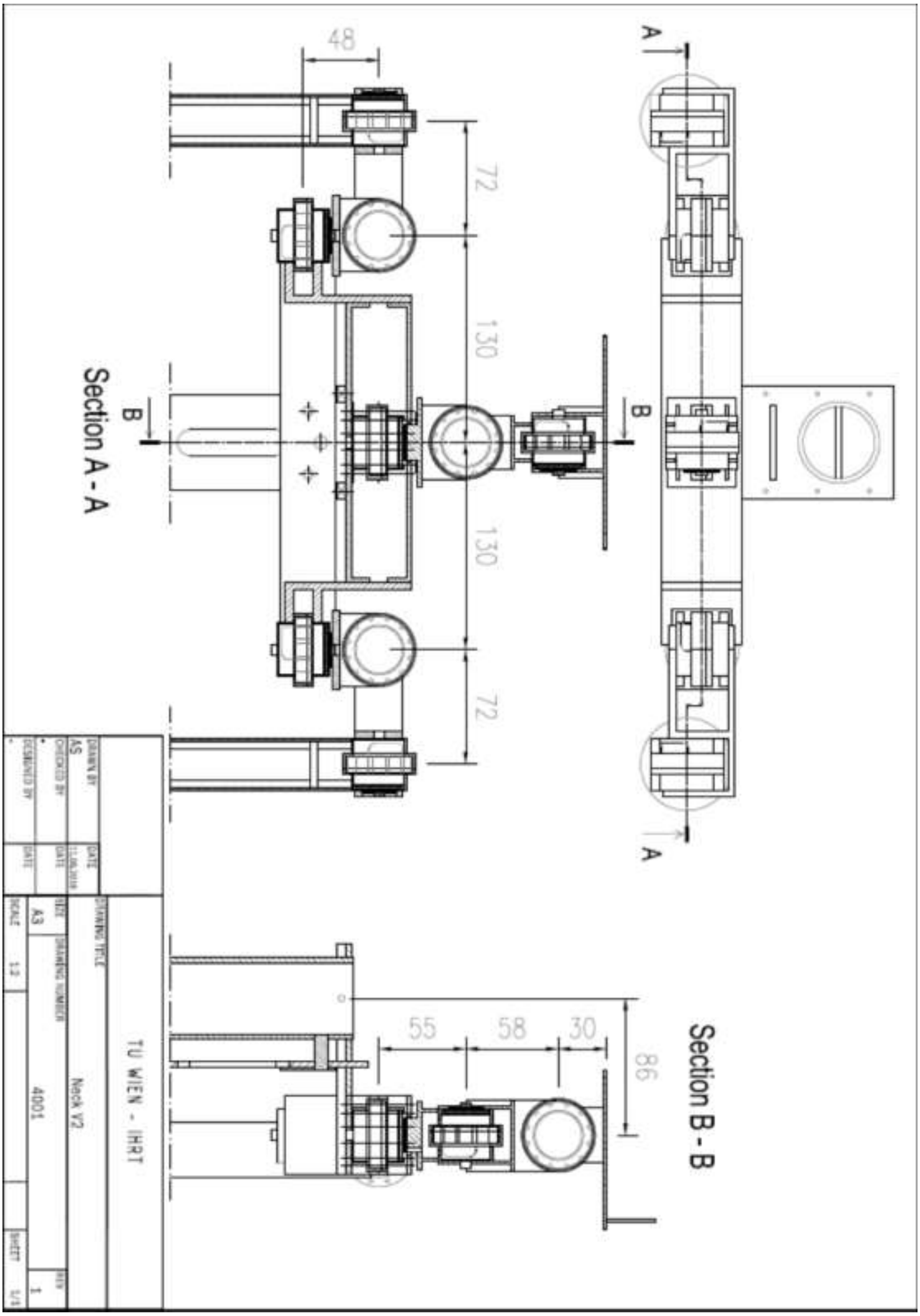


Figure 6-3. The design of Neck V2

6.3 Shoulder of V2

For this robot three revolute joints are placed on the shoulder. Actuators 1, 2 and 3 give the shoulder 3 DOF (degrees of freedom).

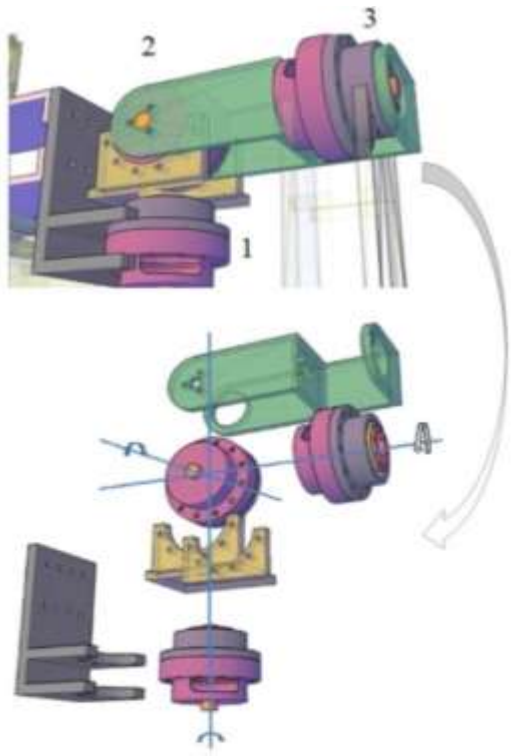


Figure 6-4. Robot arm at the part of the shoulder V2

Robot shoulder (Fig. 6-4 and Fig. 6-5) contains a motor number 1, helping the arm to make *Pitch* movement, whereas motor 2 makes *Roll* movement, while the third makes *Yaw* moves.

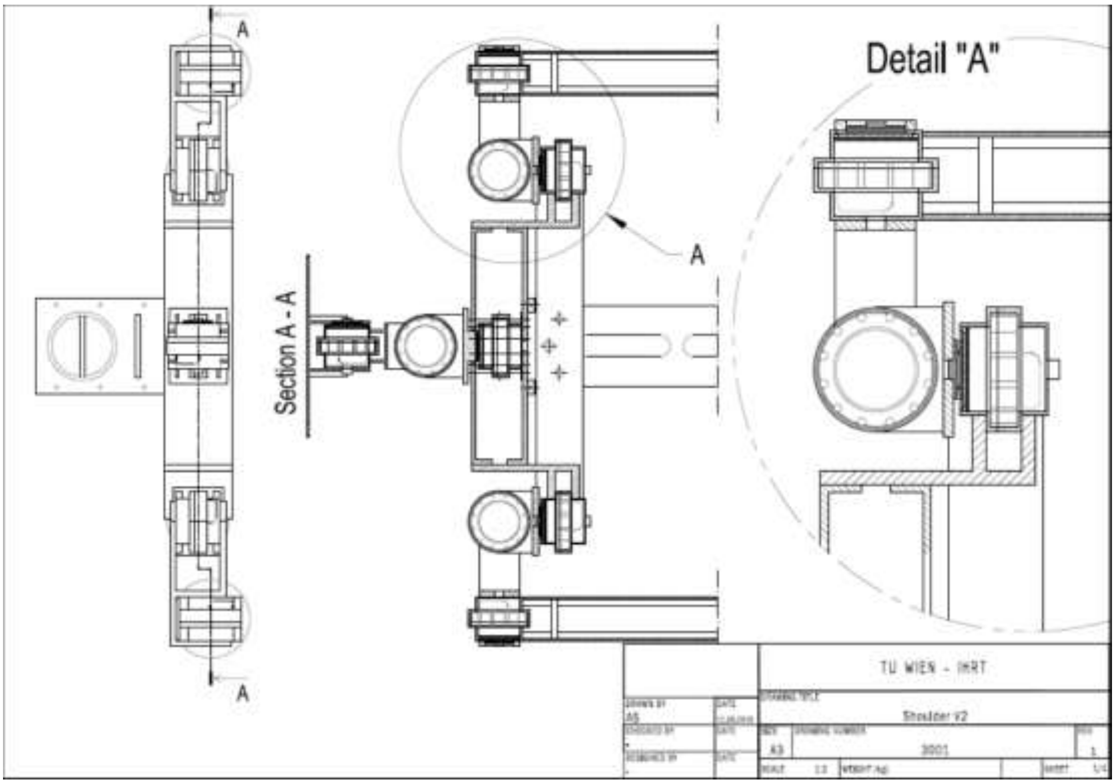


Figure 6-5. Design of shoulder V2

6.4 Arm of V2

The second prototype arm is simpler than that of the first prototype. The robot cannot stretch the arms in both sides of the body for 90 degrees, as it does at the first version. The first and second prototypes also differ completely in their arms compared to earlier proposal for Archie. At second prototype designs, brushless DC actuators are used instead of DC brushed.

*The reason for not using DC brushed ones is that they are heavy, 600**g**, they occupy large space, they use belts, and the great mass does not have a good effect in the stability of the robot, especially in the part of the arms.*

*Example: Using two DC brushed actuators, on the shoulders, and one for pan movement of the head, a mass of 3x600 = 1800**g** would be reached. Including the electrical part, only for actuators it would have a mass over 2kg. So, not using the DC brushed actuators on the shoulders, there will be enough space because toothed pulley and belts would not be used. Hence, the first prototype is more advanced, while the second prototype is simpler, but practical. The upper part contains 13 actuators. All actuators are brushless DC; the neck contains 3 brushless actuators too, ensuring 3 DOF. In the Fig. 6-6 is presented the design of the robot with prototype two of the shoulders and the neck.*

The proposed design was in PhD thesis (Mastny, 2010), but this design differs with one more motor under shoulder, it is a brushless DC. The design of the first and third prototypes is entirely different. In the shoulder of the robot, three rotational actuators have been installed, all of brushless DC type in order to perform robot arm movements, similar to human ones.

Robot arm contains 5 rotational actuators; at the wrist 1 DOF, in elbow 1 DOF, on the arm of the robot 3 DOF. Two upper limbs are connected to the neck through two parallel plates, where the basis of the neck has been placed too, inserting one motor that creates pan movement of the head.

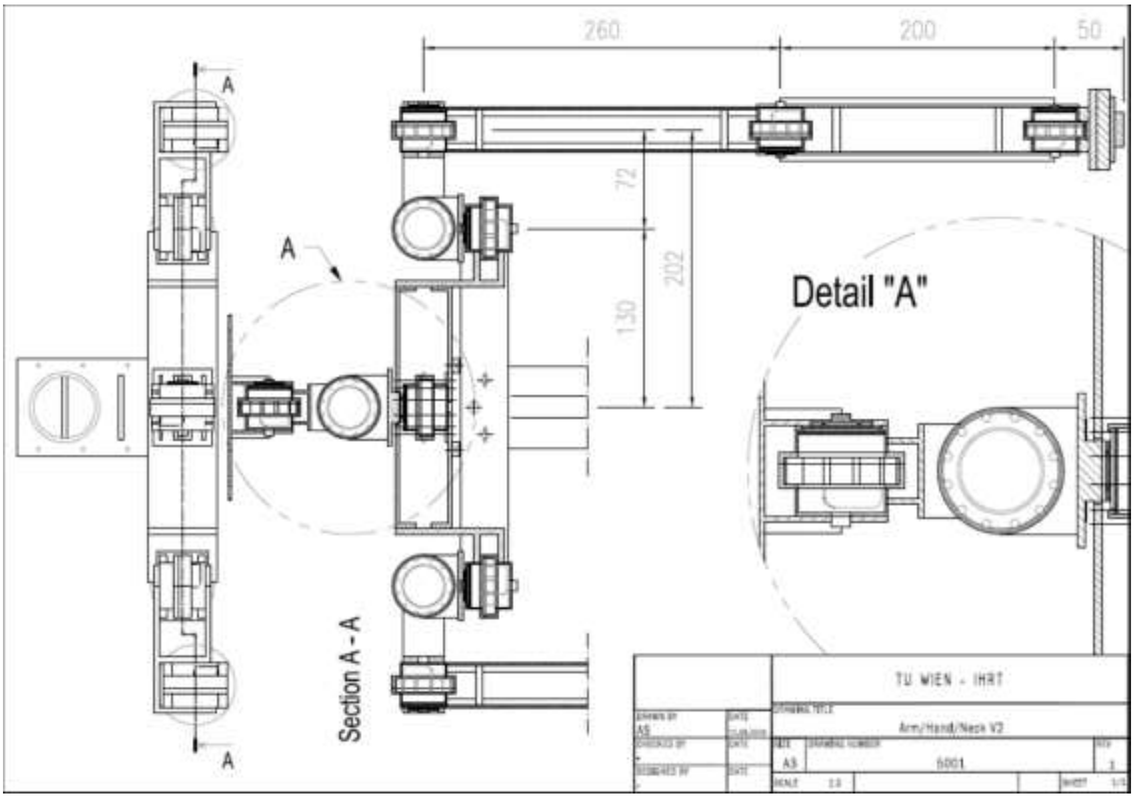


Figure 6-6. Neck, shoulders and arm V2

6.5 Marking links of V2

Naming of the links is same as in chapter 5, starting from the right hand, they are marked as U1 to U14 (Tab.6-1).

Figure (Fig.6-7) provides rotating joints of robot design of the neck, and the length of the marked links. Reference system of X, Y, Z coordinates placed on the right leg.

The table below provides names of links, and their lengths of the second prototype, from the already constructed robot limbs (Tab 6-1).

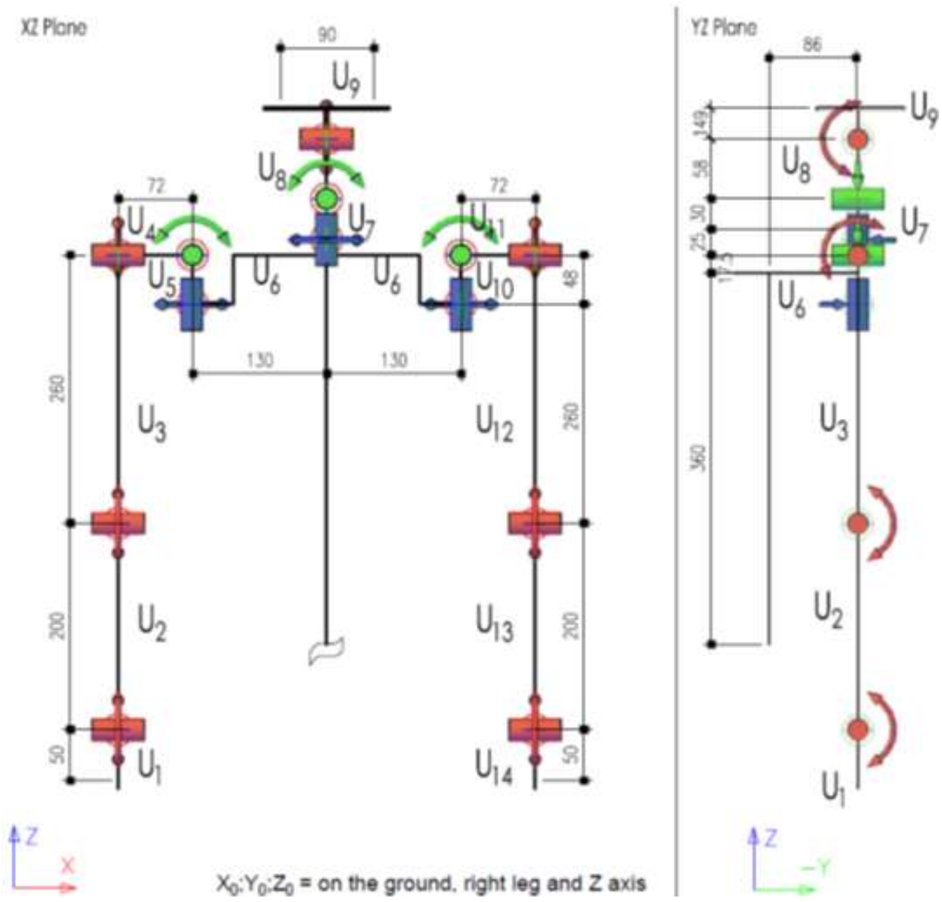


Figure 6-7. The figure provides rotating joints V2

Table 6-1. The table gives names of links, and their length

Link's name	**Length (mm)**
U1(U14)-hand (fore wrist)	50
U2(U13)-lower arm	200
U3 (U12)-upper arm	260
Length of arm-total	**510**
Shoulder	
U4 (U11)	72 (2x72=144)
2xU6	2x130=260
U10 (=U5)	48, (2x48=96)
Total shoulder length	404

Notice: *Total Shoulder length is 40.4 cm taking into consideration that the length that was measured from middle of actuators, the total length of the shoulder is 40.7cm*

6.6 Center of mass (V2)

Centre of the mass of every link (arm and neck) have been presented in the Tab.6-3, while the basic reference system has been taken in the foot of the right leg of the robot as seen below.

Movable ranges are the maximum angels of movement of joints that allow the parts of robot not to collide with each other in version 2 (Tab.6-2).

Table 6-2. Movable range of upper body (V2)

Joints	***Range***
M1(θ_1)	+/-90
M2(θ_2)	+/-90
M3(θ_3)	+/-180
M4(θ_4)	+/-90
M5(θ_5)	+/-60
M6(θ_6)	+/-360
M7(θ_7)	+/-45
M8(θ_8)	+/-60

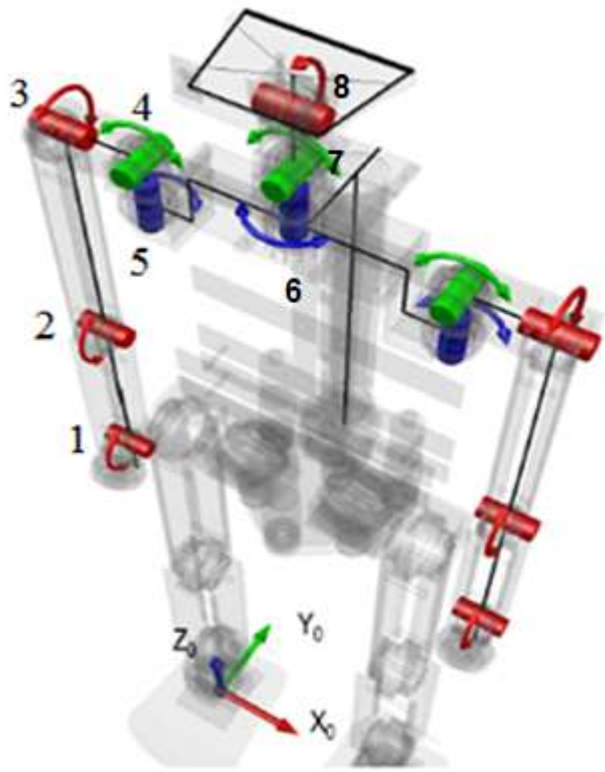


Figure 6-8. Rotary shaft of the actuators V2

The Fig. 6-8 and Fig 50-8 presented rotary shaft of the actuators while the reference coordinate system and the other part of the figure are indicated with the red colour.

Table 6-2. Link Names and Centre of Mass

Link Names	***Mass (g)***	***Centre of mass X (mm)***	***Centre of mass Y (mm)***	***Centre of mass Z (mm)***
U1	255	-72	0	615
U2	280	-72	0	740
U3	265	-72	0	970
U4	240	-45	12	1100
U5	208	0	9.40	1078
U6	770	130	21	1082
U7	119	130	9.40	1127
U8	195	130	8.80	1181
U9	161	130	2	1240
U10	208	260	9.40	1078
U11	240	305	12	1100
U12	265	332	0	970
U13	280	332	0	740
U14	255	332	0	615
Total mass	3741			

6.7 Summary

The second prototype has approximately equal weight compared to the first one, but it contains less small parts out of which the robot is constructed. Thus this design is simpler, more practical and all its joints are rotating.

7 Design of third prototype

"Nothing in life is to be feared, it is only to be understood"
Marie Curie

7.1 Introduction

This chapter presents the design of third prototype, which has been designed with two types of actuators: Dynamixel RX-64 in arms and RX-28 in neck/head. A detailed description of this design has been made, giving the most important parts of the design, and its physical appearance, dimensions, and the movable range of joints. Characteristics have been briefly provided for the actuators, and the prices.

7.2 Motors used in V3

Following the proposal of Dynamixel actuators, for the design of the upper part of Archie, due to their low price and the simplicity for assembling of them, the design of the third prototype is entirely different from two other prototypes. It is distinguished by simplicity of design, light mass, then it is distinguished for its actuators which are Dynamixel RX-64 which give nominal torque 6.4 Nm. The head/neck part is built of short links and low mass, thus the actuators do not have a heavy load. In the joints of the head area, two RX-28 actuators are placed, providing a sufficient torque for neck/head movement (User's Manual Rx-28, 2007).

Dynamixel have been proposed earlier as well, for the upper part of biped robot (Byagowi, Kopacek, & Baltes, 2011). The mass of all actuators is 1.144 kg. The same Dynamixel RX-64 and RX-28 actuators have been proposed earlier for Archie too. Such actuators have also been used at some robots such as the case with the robot CHARLI (Han, 2012). However, this design contains specifications varying in size and view in general. The three designed prototypes are of the same size.

7.2.1 Specifications of Actuators

Dynamixel actuator consists of; speed reducer, controller, driver, network function within an integrated module. Actuator Rx-64 is used on the shoulder of the provided design, and they are connected to each other in Daisy Chain. Rx-28 are installed on the neck / head area, and they give a torque of 3.77 Nm if they are supplied with a voltage of 16V, while when they are fed by voltage of 12V they provide the value of torques equal to 2.8 Nm. The recommended value of voltage is 14.4 V. The angle of the position of the shaft-axle of the motor is measured through potentiometer of a linear resistance, which has not been fixed mechanically, in a way that it allows limitless rotations. Within the servomotor there is a resistor used which is connected in serial way on the motor, while the voltage is measured through analogous input of controller. Communication between Rx-28 (Rx-64) and Main controller is carried out through sending and receiving the data.

Table 7-1. Specifications of RX-28 (User's Manual Rx-28, 2007)

Motor	**Dynamixel RX-28**	
Mass (g)	72	
Dimension (mm)	35.6x50.6x35.5	
Gear Reduction Ratio	1/193	
Applied Voltage (V)	12 V	16 V
Final Reduction Stopping Torque	2.87 Nm	3.7 Nm
Speed (Sec/60degrees)	0.167	0.126
Communication Speed :	7343bps ~ 1 Mbps	
ID: 254	ID (0~253)	

Table 7-2. Specifications of RX-64 (User's Manual Rx-64, 2006)

Motor	**Dynamixel RX-64**	
Mass (g)	125	
Dimension (mm)	40.2x61.1x41.0	
Gear Reduction Ratio	1/200	
Applied voltage (V)	15 V	18 V
Final Reduction Stopping Torque	6.31 Nm	7.5 Nm
Speed (Sec/60 degrees)	0.188	0.157
ID:254	ID (0~253)	

The data in a form of instructions (Instruction Packet) is sent from Main controller to the motor, and vice-versa the Main controller is informed through Status Packet. Rx-64 is fed with voltage of 16V to 21V, but recommendation is for 18V (User's Manual Rx-64, 2006).

Network - Every Dynamixel in network has the unique ID and it communicates in networks through; TTL, RS485, and CAN. Documentation available on Dynamixel provides explanations in detail about method and protocol of communication and data transfer to the Main Controller. Rx-64 and Rx-28 are equipped by optional frames, giving the possibility to assemble actuators to the mechanical parts of the robot. General properties have been provided on the table below.

7.3 Price of the upper part V3

The price of actuators, given by manufacturers for Dynamixel RX-64, is approximately € 300, price for RX-28 is € 210. While the total price for all actuators is approximately € 3000 (2xRX-28 for Neck/Head, 8xRX-64 for arms). With V3 is marked prototype three.

7.4 Mass distribution of V3

Distribution of mass and dimensions are given. Design and other details are given in appendix for this prototype.

The total mass of the upper part is 1,788 kg, with distribution in symmetrical manner to the ridge of robot (Fig. 7-1). Forearm has the mass of 0.144 kg, arm 0.194 kg, the part between the arm and shoulder 0.176 kg. Motor 3, Dynamixel RX-64 type, must lift the mass of the arm which is 0.379kg, with a sufficient torque of 6.31 Nm (User's Manual Rx-64, 2006). This is the maximum mass that motor 3 should keep when the arm raises aside. Motor 2 bears the mass of the arm (0.514kg.), while the arm of the robot moves while walking.

Neck/head has the mass of 0,229 kg, while motor 5 has the maximum load (mass of 0.157 kg) during movement when it carries out *pan* movement (movements on the right and left side). Dimensions of lengths of every constituent part are given in Fig. 7-3, Fig.7-4 and Fig.7-5.

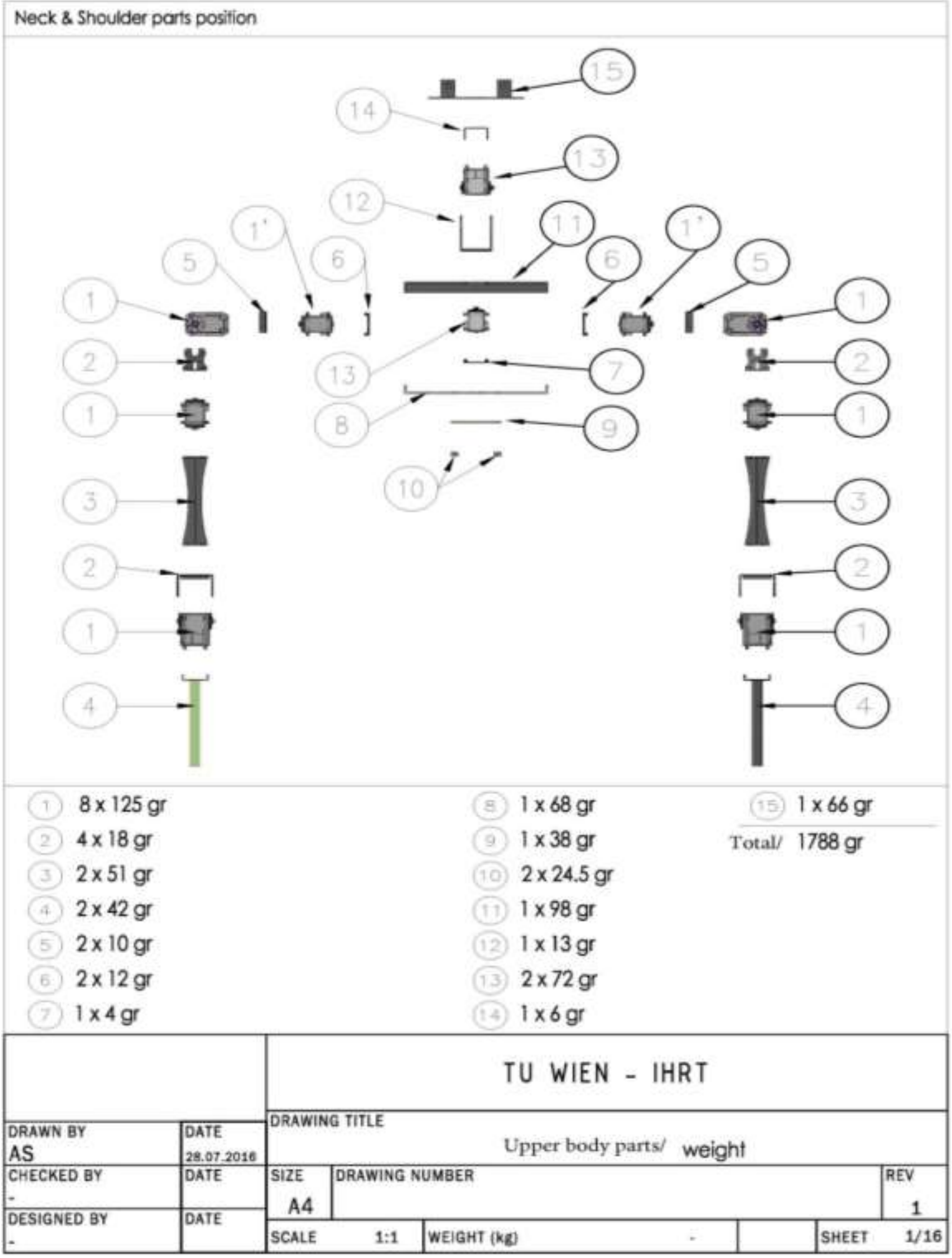


Figure 7-1. Distribution of mass of the upper body V3

7.5 Structure Design of V3

Number of RX-64 actuators that will be mounted on the shoulders of the robot is 8 (4x2), 4 actuators on one arm and 4 on the other arm. Fig. 7-2 presents the physical frontal and back view of the design of prototype three (version three V3). The arms of the robot and thorax are attached to the ridge of the robot. N1 and N2 refer to two links of neck/head.

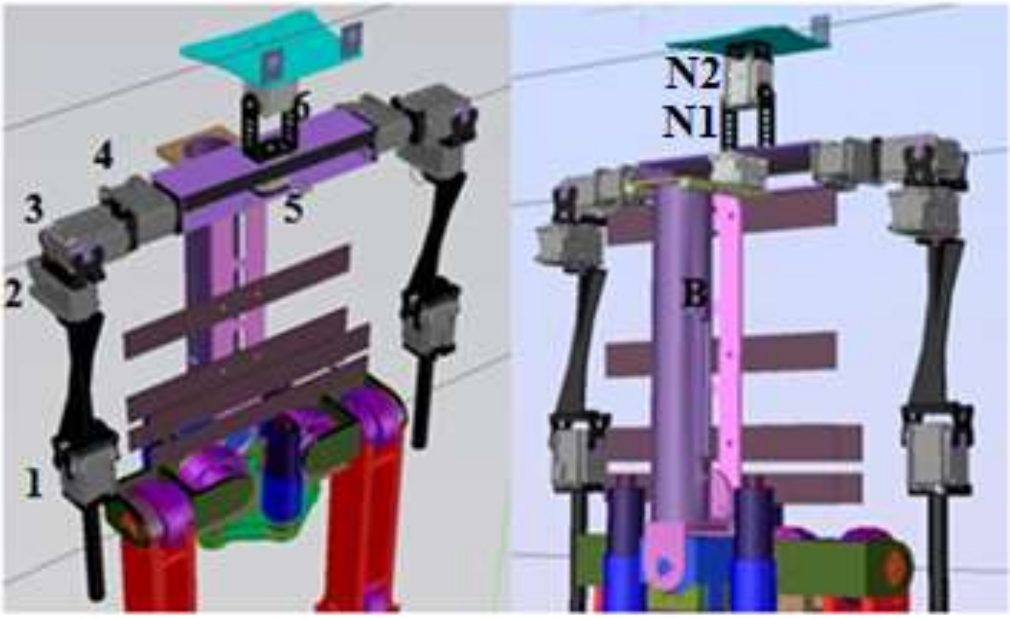


Figure 7-2. Third prototype of Archie

In addition to actuators and simplicity, the proposed design also differs for its small number of actuators. Number of actuators has been reduced for 3, unlike the other two prototypes. This design does not have a motor in the wrist position, whereas in the position of neck/head it has only 2 actuators (2 DOF) marked with numbers 5 and 6 (Fig 7-2). This design has a low price and low mass; it has been designed to have sufficient space for assembling and disassembling the equipment of the robot. While there are 13 actuators for the upper body in prototypes one and two, for third prototype 10 actuators have been given (2 actuators for Neck/Head, 2X4 actuators for arms).

7.6 Shoulder of V3

Three Dynamixel actuators are used in design, they are mounted in the position of the shoulder. The shoulders have 3 DOF (degrees of freedom), marked with numbers 2 (Pan movement), 3 (Roll movement) and 4 (Tilt movement), see Fig. 7-2 and in Fig 7-3. The fourth motor is used in the position of the elbow (marked by number 1).

All the mechanical structure of the upper body stands attached to the back (backbone) that has a cylindrical shape marked in Fig 7-2, by letter B.

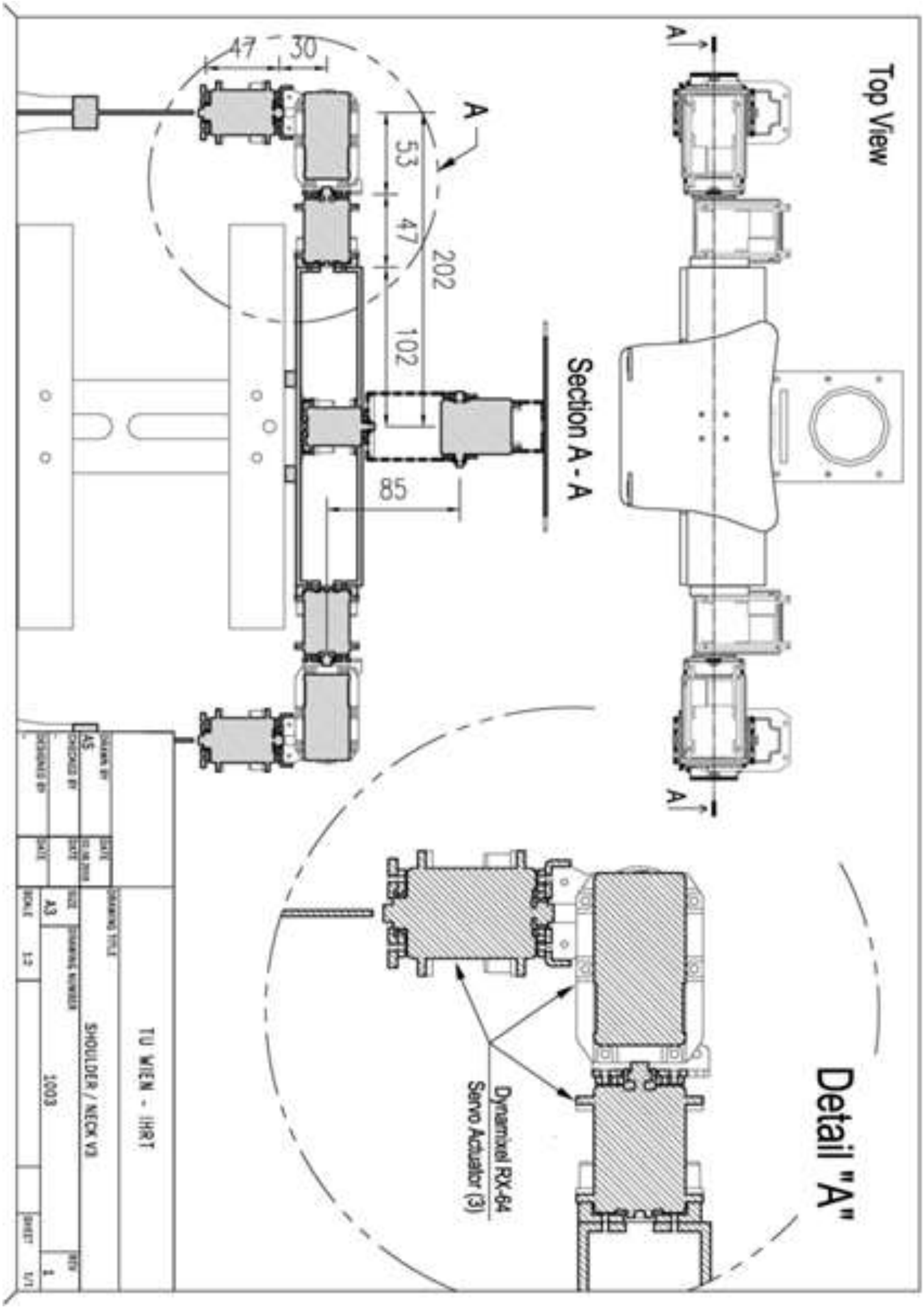


Figure 7-3. Shoulder of V3

7.7 Head of V3

The three prototypes have the same neck length, but they differ in terms of length of the links building it. The third prototype in the same length, at the part over the level of shoulders, has two links installed sharing one joint. V3 has longer links of the neck than V1 and V2. While the two prototypes V1 and V2 in that lengths of neck share three links.

In the third prototype, the neck/head has only two actuators, consequently, only two joints that provide 2 DOF given in Fig.7-4. Abbreviation V3 stands for the third version or prototype designed for robot. Neck is a structure with short links N1 = 8.5 cm whereas N2=7.5 cm. Dynamixel RX-28, has a nominal torque of 2.87 Nm (Newton meter), which is enough to raise the mass of the arm as seen in Chapter 11.

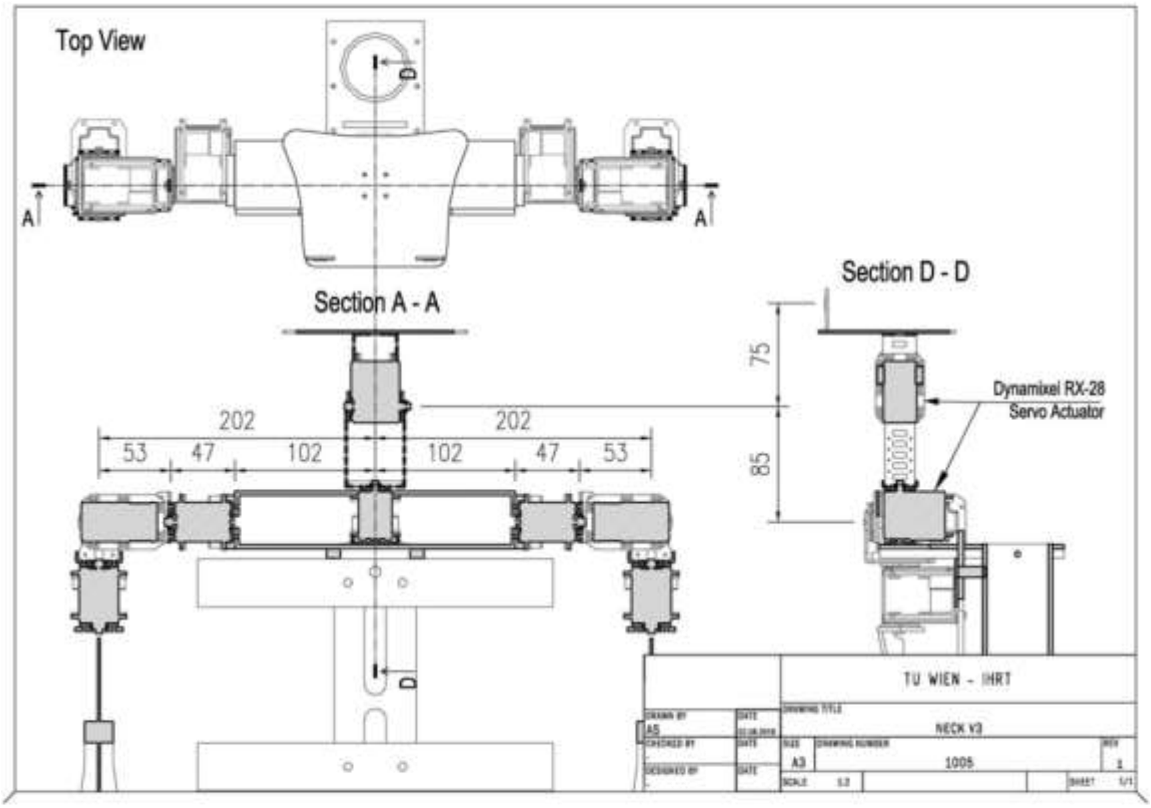


Figure 7-4. Neck/Head V3

These two joints enable sufficient movement for robot head orientation in the surrounding environment to direct the cameras. The joint where motor number 5 is installed has a movable range (+/- 360), so that it performs p*an* movement. Motor number 6 makes Tilt (Pitch) moves, with range (+/to -90). Angle of movement of actuators is determined by movement we want the head of the robot to make.

7.8 The arm of the third prototype

The arm of the third prototype includes the shoulder, arm and forearm. The part of the elbow has been provided in the design magnified in detail 'B', as well as the entire arm and lengths of each part constituting it. In this design no motor has been installed on the wrist, but in future projects it can continue with installation of actuators and the hand (Fig. 7-5).

Design of upper body performs moves of the arms while walking and has sufficient DOF (degree of freedom) to make any other movement similar to human. In addition to providing cross cuts and dimensions, the design also provides shoulders and head of the robot, seen from top view position, and the manner of putting in order the actuators of arms. Length of the arm is 46 cm.

7.9 Torque of arm and motor properties

All calculations also apply for the design of the third prototype. While two prototypes; the first and the second prototype have approximately equal mass of the arm and of the upper part, so calculations apply for both prototypes. The third prototype of the upper part has lower mass (1.788 kg) than the two prototypes (V1 and V2 are about 3.5kg - 3.7 kg), design made for Dynamixel type actuators. The actuators have been proposed due to the lower cost, and simpler use. The features of Dynamixel RX-64 motor provide as output values a torque of over 6.4 Nm, which is sufficient to afford the mass of the arm of the third prototype.

Moreover, it can afford the other dynamic values which become important during movement, such as; acceleration, inertia, and the Coriolis force. The mass of the arm (prototype 3) of the robot is over 700 g, including electrical equipment, wires and controllers.

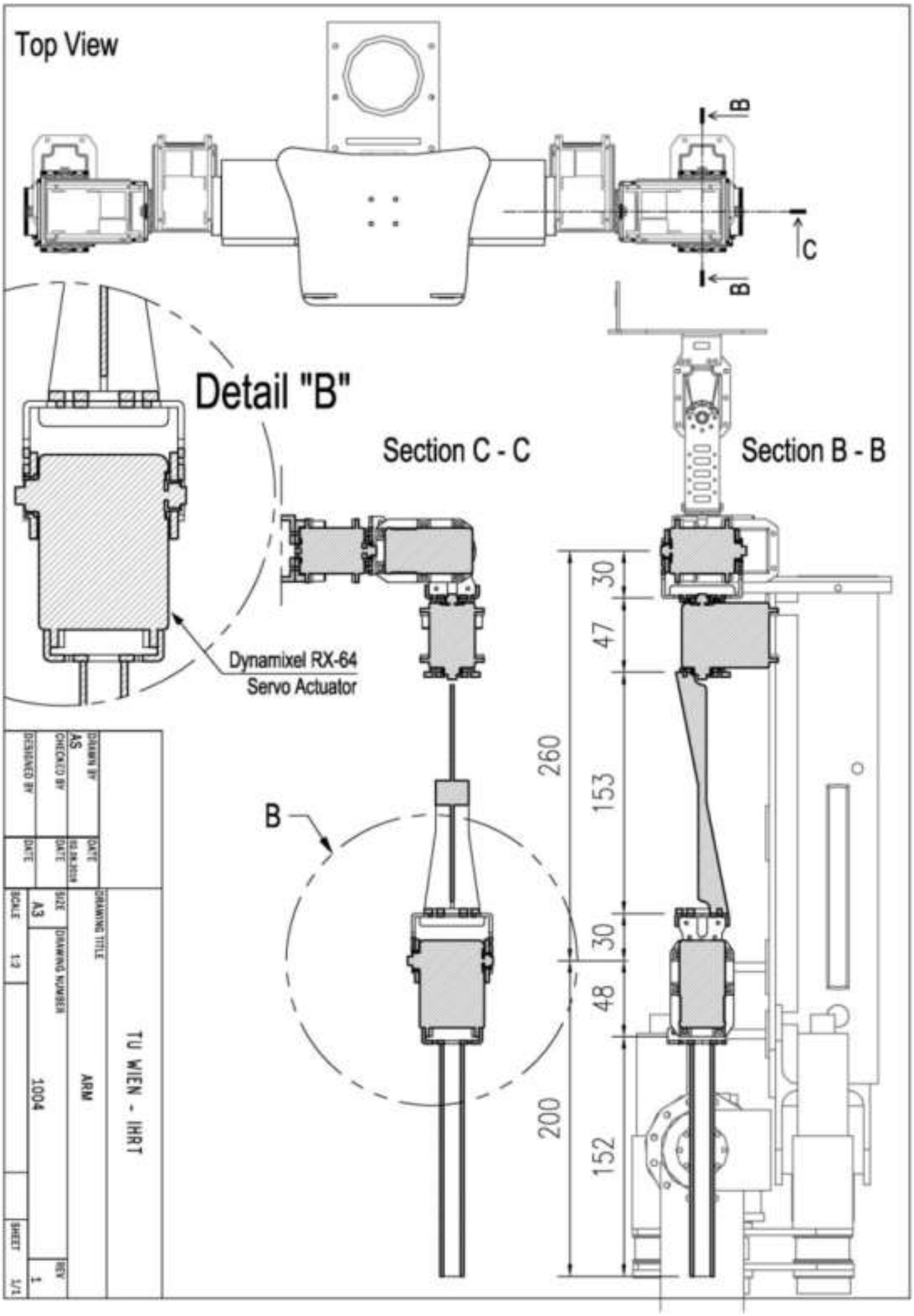


Figure 7-5. The arm of the third prototype

7.10 Static torque of the arm (V3)

Given that in all elaborations, measurements, calculations, the most suitable value is given by version three. With the same conditions for the extended arm that forms angle of 90 degrees to frontal plain. Based on the dimensions given in Fig 7-5 of version 3 and distribution of mass given in Fig. 7-1, the approximate calculation of static torque have been given (Fig 7-6). The forearm has an increased mass for 158 g, namely from 42 to 200 *g* during static calculation, to take the high values.

$\boldsymbol{\tau_{st4} = \tau_{M3} + \tau_{M2} + \tau_{arm} + \tau_{M1} + \tau_{forearm}}$=1.14 Nm. **(1)**

From the formula $\tau_{M3,}\tau_{M2,}\tau_{M1}$ marking the torque for actuators, motors have equal weight, when calculating they are marked as M1, M2 and M3. Lengths of the links have been taken from the design.

Symbols in formula present;

- L1 - length of the link from M4 to motor M2,
- L2 - length of the link from M2 to M2 representing the length of the arm
- L3, the length of the forearm.
- τ_{arm}, $\tau_{forearm}$ torque of arm and forearm.

For calculation in dynamic conditions, the maximum value t=1.95 Nm has been taken, whereas static torque is maximal t=1.14 Nm, their difference is 0.81 Nm.

At each position of the arm, value θ_4 (joint 4) is different, but $sin\theta_4 \leq \mp 1$. By multiplication $sin\theta_4$ withτ_{st4}, a different smaller value of torque is given.

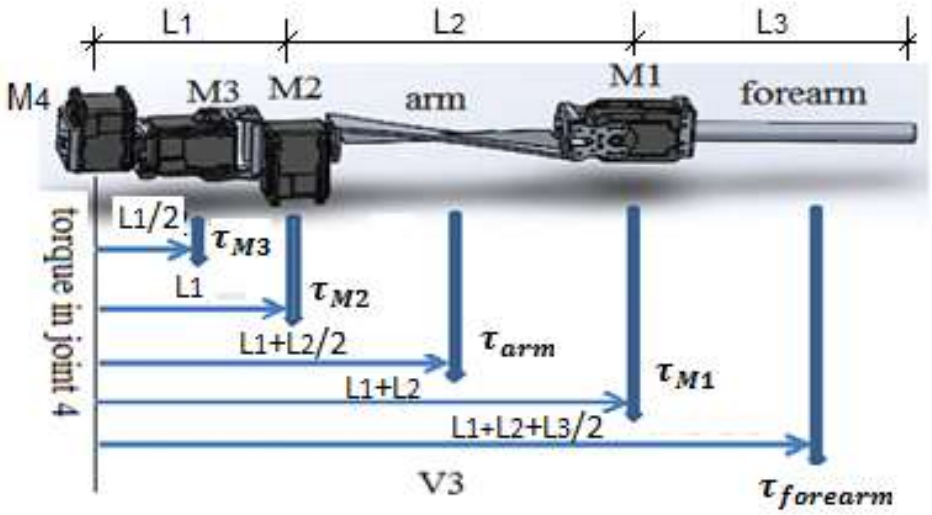


Figure 7-6. Static torque of arms V3

Conclusion; obviously, considering that the third version of upper body has half mass of version 2, from this the mass of the arm is lighter. Dynamixel actuators RX-64, with a torque over 6.4 Nm are suitable. Actuators put in motion the structure of arm, even if the robot carries on its hand, a mass of nearly 300 *g*.

7.11 D-H Parameters (V3)

Denavit –Hartenberg parameters of the Arm and Neck (V3) (Tab. 7-3).

Table 7-3. D –H parameters of the Arm and Neck (V3)

Links	**θ_i**	**α_{i-1}**	**a_{i-1}(mm)**	**d_i(mm)**
1	θ_1	90^0	0	76,5
2	$\theta_2 + 90^0$	90^0	53,5	0
3	$\theta_3 + 90^0$	90^0	0	206,5
4	$\theta_4 + 90^0$	0	200	0
Neck/Head V3				
1	$\theta_1 - 90^0$	-90^0	0	85
2	θ_2	0	75	0

7.12 Hardware architecture of V3

Software architecture for the upper part of the design of the third version (V3), where Dynamixel actuators have been selected, platform C++ is used, developed for testing and command of Archie in LINUX operating system. Interface supports the low level of hardware for communication of equipment with one another. Low Level consists of motors and micro controllers that communicate in the order with servos and sensors (except cameras, IMU, force sensors etc. can also be used). High level consists of Main Controller board (NVIDIA board) applying C++, controlling the angular displacements of shaft of Servo Dynamixel motors, cameras commanding with Low-level.

Usually change of the angles of joints gives a movement that goes through a predetermined trajectory. Trajectory represents the way through which the end-effector goes as the last point of chain of links; being cameras on the head and the hand (end effector), representing the end of links that build the arm. Preliminary calculations are made by creating models to be written for commanding in C++ language.

Various new controllers can be chosen for use in the upper body of the robot. Controllers such as CM-700 and CM- 900 have capacity to command several Dynamixel actuators in one controller. For 10 actuators of the upper part of V3 design, only three controllers can be used. Controllers are mediators in communication between actuators and the main electronic board.

There are various controllers in the market and they can be chosen with a suitable price to meet this condition, having sufficient capacity, so that one controller may have 3 or four motors under responsibility. For example commanding of the neck (which consists of two actuators RX-28) in low level can suffice with one controller.

Servo actuators Rx-28 and Rx-64 contain sensors, interface communication, processing unit and mainly components installed in printed boards, on a laminated plate with components connected with copper mounted within actuator.

Setup of the original Rx-28 and Rx-64 servo actuators consists of the Processing Unit AVR ATmega for processing data by obtaining it from Communication Interface through Transceiver. Servo Motor Driver is fed by Electrical Power input, whereas Processing Unit is notified of the voltage at input from the Voltage Sensor. For temperature of motor the information is received through the Temperature Sensor (User's Manual Rx-64, 2006) (User's Manual Rx-28, 2007).

The Processing Unit Servo Motor Driver – regulates displacements in Gearbox, which provides a Mechanical Power Output. Data processing unit processes the data and desired values, controlling the actuators. Transceiver and serial interface of the processing unit uses bus configuration with high compatibility for control with multiple operation of actuators (User's Manual Rx-64, 2006).

In all joints in this design, they are rotational; in version three (V3) motors in the upper body are brushless Dynamixel (Rx-28 on the neck/head, RX-64 in arm) which can be connected with two controllers (depending on processing needs and number of sensors). Controllers mediate the motors and Main Controller, where all controllers and cameras are connected. Central controller is installed on the chest of robot, communicating with majority of equipment through CAN bus. Actuators Dynamixel (Rx-28) are located on the neck, consisting of 2 DOF. Axis of the joints on the neck make up the straight angle, and the arm of V3 (prototype three) has 4 DOF. Axes of joints are crossed forming straight angle too. These actuators on the neck and on the arms are connected to each other through interface. They can be used for controlling PID controller for tracking task. To build a more complex system of control and to have accurate and controlled movement, in addition to cameras, other sensors are also used with enhancement of the robot, such as; touch sensor, force sensors, IMU, etc.

Angular position of motors is read by sensors located on the Dynamixel servomotor, and from these values the position of end-effector can be calculated. Characteristics of actuators and controllers of V1, V2 have been discussed, and also the characteristics of motors of prototype three (V3). Usually processors used at different robots include; Pentium III-M processors, PCI-104, 1.6-GHz Intel Atom Z530, DSP controller, Dual-Core AMD E-450 1.65 GHz, Atmel ATmega328P microcontroller etc. At some robots PCs and laptops with powerful processor are used, such as Intel i8, Intel i7 etc., depending on the type and number of equipment they are used.

7.13 Interface of V3

Neck/Head of third version, is mainly simple, built of a light material, with a mass of approximately 230 g. Type of controller that will be used can be whatsoever depending on PID controller using the appropriate parameters that have been selected.

Parameters of the controller are defined through measurements, comparisons, simulations, setting up for the most suitable conditions. Controllers can be used at actuators Dynamixel Rx-28 being large and available in market in different prices and qualities**.**

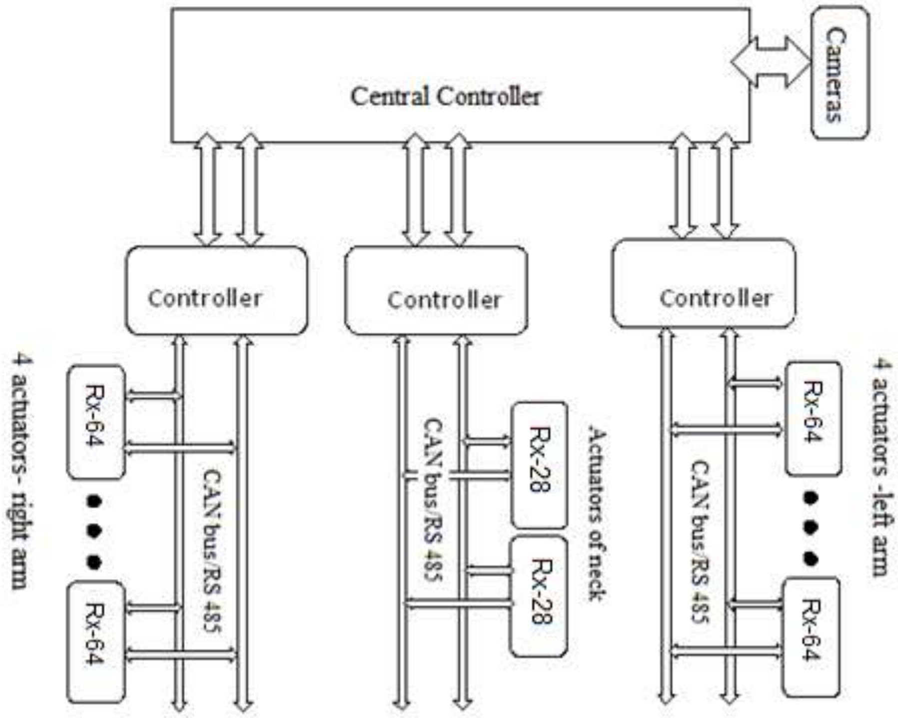


Figure 7-7. Block Diagram of connections Dynamixel actuators

Neck is commanded directly by the Main Controller, but its work is loaded, as cameras during the data processing take a large space of processor. Actuators are connected with the main controller through sub-controllers (CM-700, CM-900). In the diagram (Fig.7-7) presented below, actuators of the neck are Dynamixel Rx-28, located on the joints of Neck/Head of third prototype marked by abbreviation V3. Upon completion of the design, mechanical calculations, and choosing the necessary hardware, construction of mechanical structure, the motors are mounted**.** Following selection of other electronic equipment comes the part of control of this structure. The real systems consist of a multi input-output approach, which comes from the system consisting of many sensors collecting information on the system state in the output.

The dynamic systems are controlled by a series of parallel systems so that a certain trajectory of arm, head or feet movement of the robot is obtained, associated with a desired speed. Therefore considerable preliminary calculations are required. Several patterns for stabilization of robot head movement are recognized, such as; Inverse Jacobian controller, inverse kinematic controller, FEL controller etc. The controller patterns can be applied in upper body movements (Falotico, et al., 2016), (Falotico, et al., 2012).

7.14 Summary

The description showed the simple shape of design, actuators of low price and practical shapes for assembling. This part has provided distribution of mass at prototype three, and characteristics of selected actuators. Actuators are suitable, as they are available with their parts for connection to the parts of skeleton of the design.
They have a plastic case containing a gear reduction, thus there is no need to calculate or build the harmonic drive part. This design is cheaper, more suitable for Archie and has a lighter construction. This design is practical as it does not have small parts and does not have many bolts for connection of pieces to each other. This chapter provides the characteristics and the design presenting the entire prototype 3. Third prototype features have been entirely described. V3 has a much lower weight compared to V1, V2, and all other features are more suitable. Actuators consume less power, while vibrations when moving the limbs are much smaller.

8 Calculation of V2

"The path is a spiral; we have already climbed many steps."
Hermann Hesse

8.1 Introduction

This part provides a mathematical description of arm of the robot with matrix of transformation. Coordinate systems of neck and arm of the robot have been presented, and the parameters have been found according to Denavit Hartenberg convention, thus gaining the equations for finding the torques. Masses of arm and neck have been given, and the moment of inertia too. Fig.8-1 presents the image and the systems of coordinates of the joints in compliance with (D-H) Convention, placed on the joints connecting the links forming the arm, whereas at figure (Fig. 8-4) the neck coordinate systems have been provided. From this, matrices of transformation of Archie arm and matrices of neck transformation have been obtained. The necessary calculations were made for selecting the needed motors and calculating the torque and moment of inertia.

8.2 Equations of arm and neck

Dynamic features of robot arm and neck depend not only on physical characteristics of construction of the design but also on the dynamic model, presented in control algorithms obtained by the dynamic model. That enables to reach the wanted response of the system. Arm consists of 5 rotating joints, while in the case of neck there are 3 rotating joints. Also in the second prototype of the neck there are 3 joints, but only one of them is rotational while 2 others are translational joints. In the platform where cameras are mounted in the same levels, there is a passive joint which does not obstruct the movement of the platform. The simplest case for the neck in question is the serial neck with three rotating joints. All estimates are simple when the kinematic parameters are known.

Dynamic values such as position, speed, velocity and the rotating moment can be found. The robot body consisting of links (that builds the arm and the neck) is put in motion by the actuators, the power faces; non-linearity, loads of inertia, friction in joints and between the links, the mass of links, as well as the load of gravity. The dynamics of arm and neck of the robot are also described by Newton - Lagrangian mechanics. Mobility of arm and neck is provided in the form of matrix equation. Marked symbols of the equations of movement and elaborations for D-H convention have been taken the same as in the book *'ROBOTICS: Control, Sensing, Vision, and Intelligence'* (Fu, et al., 1987).

According to Lagrange-Euler movement equation;

$$ {}^{\mathbf{d}}/_{\mathbf{dt}}\left({}^{\partial\mathbf{L}}/_{\partial\dot{\mathbf{q}}_{\mathbf{i}}}\right) - {}^{\partial\mathbf{L}}/_{\partial\mathbf{q}_{\mathbf{i}}} = \boldsymbol{\tau} \qquad (2) $$

L= Lagrangian function $L = K - P$, while L represents the difference between the total Kinetic energy and potential energy where $P = \sum_{i=1}^{n} -m_i g\left(A_i^0 r_i^i\right)$, i=1,2,...n., m-mass of links, A-matrix of transformation, constant value g- gravitation force, according to axis of systems of coordinates there are $P = \sum_{i=1}^{n} -m_i g\left(A_i^0 r_i^i\right)$, i=1,2,...n., m - mass of links, A - matrix of transformation, constant g - force of gravitation, where according to the axis of system of coordinates $\left(g_{x,}, g_y, g_z, 0\right)$, whereas the radius of the system of coordinates of the joint that *i-th* has been marked by $P = \sum_{i=1}^{n} -m_i g\left(A_i^0 r_i^i\right)$, i=1,2,...n., m - mass of links, A- matrix of transformation, constant g- gravitation force, where the axis of system of coordinates are $\left(g_{x,}, g_y, g_z, 0\right)$, whereas the radius of the system of coordinates of the joint that *i*-th has been marked by r_i^i.
K-total kinetic of the robot arm, neck/head

$$ \boldsymbol{K_i} = {}^{\mathbf{1}}/_{\mathbf{2}}\left[\sum_{p=1}^{i}\sum_{r=1}^{i} \boldsymbol{U_{ip}}\left(\int \boldsymbol{r_i^i r_i^T dm}\right)\boldsymbol{U_{ir}^T \dot{q}_p \dot{q}_r}\right] \qquad (3) $$

The expression within small brackets is the inertia of all rotating joints, where

$$ \boldsymbol{J} = \left(\int \boldsymbol{r_i^i r_i^T dm}\right) = \begin{bmatrix} \int x_i^2 dm & \int x_i y_i dm & \int x_i z_i dm & \int x_i dm \\ \int x_i y_i dm & \int y_i^2 dm & \int y_i z_i dm & \int y_i dm \\ \int x_i z_i dm & \int y_i z_i dm & \int z_i^2 dm & \int z_i dm \\ \int x_i dm & \int y_i dm & \int z_i dm & \int dm \end{bmatrix} \qquad (4) $$

By the partial derivative of the first row matrix obtained by D-H convention A, with a variable $\theta i = qi$ for the case when rotating joint, then $\theta i = qi$ for the case when having rotating joint. Then${}^{\partial^{i-1}A_i}/_{\partial q_i} = Q_i A_i^{i-1}$. The matrix $\theta i = qi$ for the case when there is a rotating joint. Then${}^{\partial^{i-1}A_i}/_{\partial q_i} = Q_i A_i^{i-1}$. Matrix Q_i is noted according to variables, might be rotating, prismatic, but in our case for the rotating joint, this matrix is obtained as a result of differentiation for $\theta i = qi$ for the case when rotating joint is ${}^{\partial^{i-1}A_i}/_{\partial q_i} = Q_i A_i^{i-1}$.

Matrix Q_i is noted as variable that can be a rotating one, prismatic, but in our case for the rotating joint, this matrix is obtained as a result of differentiation for θi matrix $\theta i = qi$ for the case when rotating joint, then ${}^{\partial^{i-1}A_i}/_{\partial q_i} = Q_i A_i^{i-1}$. Matrix Q_i is noted as variable which can be a rotating one, prismatic, but in our case for the rotating joint, this matrix is obtained as a result of differentiation for θi of matrix A_i^{i-1}, this differentiation gives the matrix $\theta i = qi$ for the case of rotating joint., then ${\partial^{i-1} A_i}/{\partial q_i} = Q_i A_i^{i-1}$. Matrix Q_i is noted as variable and can be a rotational one, prismatic, but in our case for the rotational joint, this matrix is obtained as a result of differentiation for θi of matrixA_i^{i-1}, this differentiation gives the matrixQ_i;

$$\boldsymbol{Q_i} = \begin{bmatrix} \mathbf{0} & \mathbf{-1} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \qquad (5)$$

For $U_{ij} = \{A_{j-1}^0 Q_j^{j-1} A_i$ for$j \leq i$, for other values $U_{ij} = \{A_{j-1}^0 Q_j^{j-1} A_i$ for$j \leq i$, for other values $U_{ij} = 0$.

$$\boldsymbol{U_{ij}} = \{\boldsymbol{A_{j-1}^0 Q_j^{j-1} A_i} \qquad (6)$$

For arm of the robot and its neck, in the case of all rotational joints, in the case i=j=k

$$\boldsymbol{\partial U_{ii}}/\boldsymbol{\partial\theta_i} = \boldsymbol{\partial}/\boldsymbol{\partial\theta_i}\left(\mathbf{Q_i A_i^0}\right) = \mathbf{Q_i Q_i A_i^0} \qquad (7)$$

Value ${\partial U_{ii}}/{\partial\theta_i}$ describes the influence of joints *j* and *k* on the joint *i.* It is implied that i=j=k=1, impact of joint 1 of all other joints.

Equation e Lagrange –Euler in the form of matrix we have;

$$\boldsymbol{\tau(t)} = \boldsymbol{D}\big(\boldsymbol{q(t)}\big)\boldsymbol{\ddot{q}(t)} + \boldsymbol{h}\big(\boldsymbol{q(t)}, \boldsymbol{\dot{q}(t)}\big) + \boldsymbol{c}(\boldsymbol{q(t)}) \qquad (8)$$

Symbols that constitute the equation represent;

$\tau(t)$-Torque force matrix vector *nx1*

$D\big(q(t)\big)$ Matrix *nxn,* symmetric inertial acceleration-related,

$h\big(q(t), \dot{q}(t)\big)$ Non-linear Coriolis and Centrifugal force matrix of order *nxn*. If replaced by the formula only for the rotating joint, then there will be $q(t) = q(t) = \theta_i$; q_i- General coordinates for arm of the robot, $\dot{q}_i$ First derivate of general coordinates, is the speed of joint, $\ddot{q}_i$ - Second derivative of rotating joints, expressing the angular acceleration of the joint.

In literature, the angle θ_i- is marked with q, representing the general coordinates of the joint that can be rotating joints, translational, etc.

$\ddot{q}_i$- finding values of angular acceleration of the joint for a torque value, it is done with FD.Whereas when the value of the torques is found for the given acceleration of the joint is done through the inverse Dynamics.

The first member of the equation is $D(\theta)$, for Acceleration-Related symmetric Matrix, as the neck of the robot has three joints, then the order matrix is *3x3*,

$$\mathbf{D}(\boldsymbol{\theta}) = \begin{bmatrix} \mathbf{D_{11}} & \mathbf{D_{12}} & \mathbf{D_{13}} \\ \mathbf{D_{12}} & \mathbf{D_{22}} & \mathbf{D_{23}} \\ \mathbf{D_{13}} & \mathbf{D_{32}} & \mathbf{D_{33}} \end{bmatrix} \quad (9)$$

This matrix for the case of arm, if all the five joints of the arm are taken into consideration, calculations give the order of matrix as 5x5. Then it presents $h\big(q(t), \dot{q}(t)\big)$ non-linear Coriolis and Centrifugal force for the neck that will be;

$$\mathbf{h}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) = \begin{bmatrix} \mathbf{h_1} \\ \mathbf{h_2} \\ \mathbf{h_3} \end{bmatrix} = \begin{bmatrix} \dot{\boldsymbol{\theta}}^{\mathbf{T}} \mathbf{H_{1,v}} \dot{\boldsymbol{\theta}} \\ \dot{\boldsymbol{\theta}}^{\mathbf{T}} \mathbf{H_{2,v}} \dot{\boldsymbol{\theta}} \\ \dot{\boldsymbol{\theta}}^{\mathbf{T}} \mathbf{H_{3,v}} \dot{\boldsymbol{\theta}} \end{bmatrix} \quad (10)$$

where,

$$\boldsymbol{H_{i,v}} = \begin{bmatrix} \boldsymbol{h_{i11}} & \boldsymbol{h_{i12}} & \boldsymbol{h_{i13}} \\ \boldsymbol{h_{i12}} & \boldsymbol{h_{i22}} & \boldsymbol{h_{i23}} \\ \boldsymbol{h_{i13}} & \boldsymbol{h_{i23}} & \boldsymbol{h_{i33}} \end{bmatrix} \quad i=1,2,3\ ,.. \quad (11)$$

Angular velocity of 3 joints of neck can be expressed in column vector;

$$\dot{\boldsymbol{\theta}}(\mathbf{t}) = [\dot{\boldsymbol{\theta}}_{\mathbf{1}}(\mathbf{t}) \quad \dot{\boldsymbol{\theta}}_{\mathbf{2}}(\mathbf{t}) \quad \dot{\boldsymbol{\theta}}_{\mathbf{3}}(\mathbf{t})]^{\mathbf{T}} \quad (12)$$

From equations, the torque of neck/arm is calculated.
Whereas the third member in equation of torques is $c(q(t))$ gravity loading force vector.

8.3 DH parameters of Arm (V2)

Arm of the robot consists of links connected in series with each other with rotating joints from shoulder to the wrist. One link is connected with the joint at wrist in length of 50 mm where the hand is connected. This part represents the end-effector of robot arm. In the future, depending on the design that will be selected, it can be equipped by hand. Calculation of the position and orientation (end/effector) is carried out knowing the parameters of rotating joints from Denavit-Hartenberg convention.

Description of orientation and position of end-effector (wrist) from values of variables of joints is known as forward kinematics. By knowing the kinematic parameters, different kinematic and dynamic units of the arm can be calculated. The Inverse Kinematics determines the values of angular movement of joints connecting two links from the known values of position or trajectory going through the end-effector.

Thus, this chain link of joints and links provide the overall movement of the entire robot.

The first step on the agreement of Denavit Hartenberg for finding parameters; θ_i, d_i, a_i, α_i, is arrangement of OZ axis of coordinate system in concordance with axis of rotation of joints (Fu, et al., 1987). Motors are fixed at joints with their shaft of rotation. (*i*) Denotes the number of joints. Systems of coordinates order in a way as to have as many positive values as possible at angles θi and αi, and to gain zero values as much as possible for the kinematic parameters. Because the joints of the neck and of the arm will be discussed later as they contain only two rotating joints, implying that as a variable of θ_i angle, while three other units (d_i, a_i, α_i) have constant values.

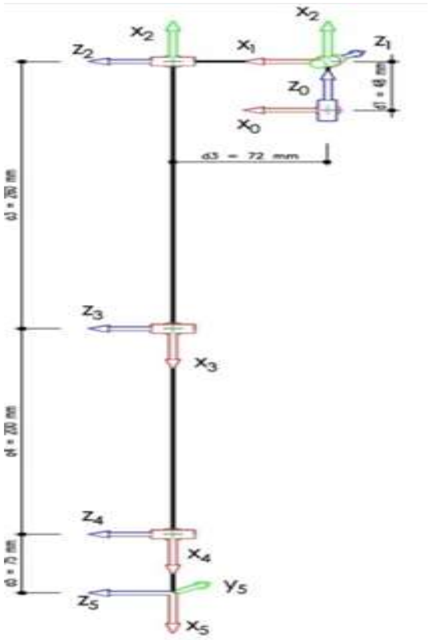


Figure 8-1. Establishing link coordinate systems of Arm

Fig.8-1 shows the systems of coordinates of arm, while the values of the Denavit-Hartenberg parameters are provided on Tab.8-1.

If the offset value of the angle =0 is taken, then it can be considered as follows Θ1=0, Θ2=-90, Θ3=-180, Θ4=0, Θ5=0. Movement of the joints can be read by Hall sensor, speed of joints is read by taco-generator. Sensors are located at the feedback part of dynamic system, they measure values at the output of the system, taking those values of measurement and bringing them to the comparator. In this way the error of values at the output of the system is found, deducting or comparing with input values.

Table 8-1 Denavit –Hartenberg parameters of the Arm V2

i	*Θi*	*di*	*ai*	*αi*
1	*Θ1*	*d1=(48)*	*0*	*90*
2	*Θ2+90*	*0*	*0*	*90*
3	*Θ3+180*	*d3=(72)*	*a3=260*	*0*
4	*Θ4*	*0*	*a4=200*	*0*
5	*Θ5*	*0*	*a5=50*	*0*

Thus, the angular movement of every joint of the robot is known. As a result, from shifts a movement of hand is obtained, or cameras at the end-effectors, and they will make a move in a trajectory of a certain shape.

8.4 Moment of inertia of arm

Moments of inertia of each link in the structure of the neck and arm of robot are calculated very easily knowing the mass of the link and dimension values. Depending on the system of external coordinates where it is taken from, the rotation happens conducting a moment of rotation force (torque), and the moments of inertia are determined. Under a) shows the centre of the mass for the entire arm with the participation of five links and joints, under b) three joints were taken into consideration, 3 links excluding two links that build the shoulder.

Figure 8-2. Arm with the coordinate systems located on the joint 1and 3

Arm with the coordinate systems located on the joint 3 under a), then in the joint 1 under b) (Fig 8-2).

Their mass and the moments of inertia are shown; it is a part that is discussed in the following chapter.

8.4.1 Moments of inertia (joint 3)

Below are presented values of inertia for the joint 3, under b); Mass = 638.80 g, Volume = 212624.36 mm^3, Surface area = 116819.96 mm^2,
Centre of mass: (mm); (X = -95.86, Y = 28.31, Z = -254.53). Moments of inertia: ($g * mm^2$) taken at the output coordinate system.

Ixx = 54171339.09	Ixy = -1733702.14	Ixz = 15584421.48
Iyx = -1733702.14	Iyy = 59547257.16	Iyz = -4660876.70
Izx = 15584421.48	Izy = -4660876.70	Izz = 6570644.25

8.4.2 Moments of inertia (joint 1).

Coordinate system 3 taken in joint 1, see Fig. 7-2 under c); Mass = 841.18 g, Volume = 277589.46mm^3, Surface area = 217951.21mm^2, Centre of mass: [X = -93.57, Y = 28.44, Z = -168.35] (mm)
Moments of inertia ($g * mm^2$): taken at the output coordinate system.

Ixx = 56573154.71	Ixy = -2232861.53	Ixz = 13772684.32
Iyx = -2232861.53	Iyy = 63356952.72	Iyz = -4055824.39
Izx = 13772684.32	Izy = -4055824.39	Izz = 8394452.72

8.5 Static torque of the arm (V2)

To find the values that the actuator must have, the static torque is calculated from that point of the arm of the robot, where it will be assembled. The motor that will have larger load will be taken into consideration.

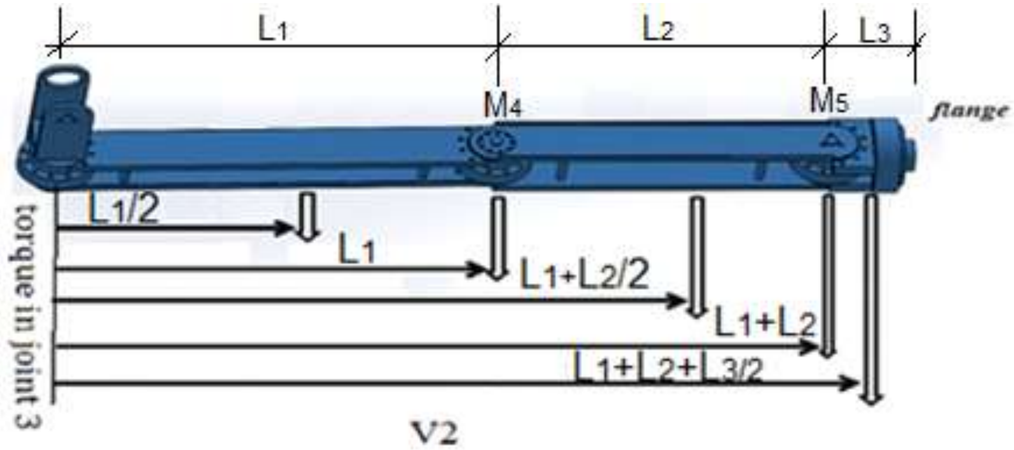


Figure 8-3. Static torque of arms V2

Knowing the mass of links and actuators, according to the data in tables from above chapters, static torque is $\tau_{st} = M * L * g\ sin\theta_i$, where *M*- mass of the motor, *m*- mass of the link, *L*- length of the link, $g = 9.81\ m/s^2$- gravitational velocity.

The arm is extended to the side in 90 degree angle. In this position there is larger load on the Joint 3. The mass of actuators is *m*= 130 g. All forces that are related to the links and motors are normal to the direction of gravitation force, where arm extends forward.

The total of all moments of the arm of the robot, representing each link and motor gives (Formula 13);

At each position of the arm, value θ_3 (Joint 3) differs, but$sin\theta_3 \leq \mp 1$. By multiplication $sin\theta_3$ withτ_{st3}, different smaller values of torque are obtained.
The values of dynamic torques are given below, for the angles $\theta_3, \theta_4, \theta_5$ marked as Joint 3, Joint 4, and Joint 5. Actuators for the mass of the arm approximately 0.85 kg, require a maximum torque no higher than 3Nm.

$$\boldsymbol{\tau_{st3} = \tau_{l1} + \tau_{M4} + \tau_{l2} + \tau_{M5} + \tau_{flange} =}$$
$$\boldsymbol{m_{l1} * \frac{l1}{2} * g + M_4 * (l1) * g + m_{l2} * \left(l1 + \frac{l2}{2}\right) * g}$$
$$\boldsymbol{+ M_5(l1 + l2) * g + m_{flange}\left(l1 + l2 + \frac{l3}{2}\right) * g = 2.22\ Nm} \qquad (13)$$

From obtained values, it is understood that brushless motors from 30 to 50 watt with one gearheads with reduction of 1:100 to 1:160, will give sufficient torque output of 8 to 13 Nm, for movement of the arm with the mass of 0.85kg. Calculations will be presented below taking into account the dynamic measures that are required during movement.

8.6 DH of head (V2)

This part explains mathematical description of the neck of robot with matrices of transformation, acquired according to Denavit Hartenberg convention. By finding the matrix of transformation based on the Denavit-Hartenberg Convention, matrices of each rotating joint have been found, and link too (Fu, Gonzalez, & Lee, 1987). Then with multiplication of matrices for each joint the general matrix is acquired expressing the connection between the base system of coordinates and the system that approved to be the end-effector. The end-effector is with the part where cameras are located, making a trajectory with the orientation of the cameras. Moves of joints give movement of the end-effector(s). For calculating the matrices of transformation, it is necessary to know dimensions of the links and the relocation in space, to each other, of the rotational joints, (Fig. 8-4).

In the table (Tab.8-2) below, from the figure the following values have been acquired for the parameters θ_i, d_i, a_i, α_i. Fig.6-3 under b) showing systems of coordinates approved according to Denavit Hartenberg convention, and the physical view, and the system of coordinates where moments of inertia are calculated. Fig.8-4 under a) presents the view of systems of coordinates of the joints in accordance with (D-H) Convention located at joints of the neck, from where matrices of transformation of the neck of Archie are obtained, with 3 DOF.

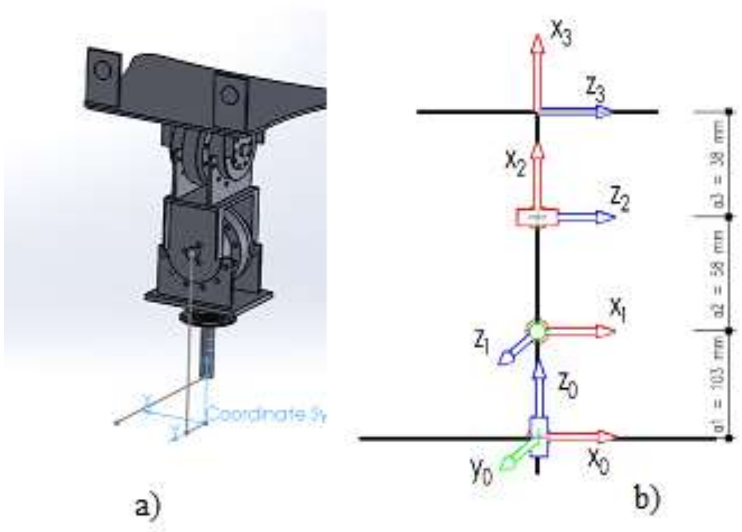


Figure 8-4. Establishing link coordinate systems for Head/Neck

Fig.8-4 under a) provides the physical appearance of the serial neck of the robot, below noted in the system of coordinates $X_0Y_0Z_0$ (joint 1), located under the first joint giving only axis in the figure. Under b) systems of coordinates approved are given according to (DH) Denavit Hartenberg Convention.

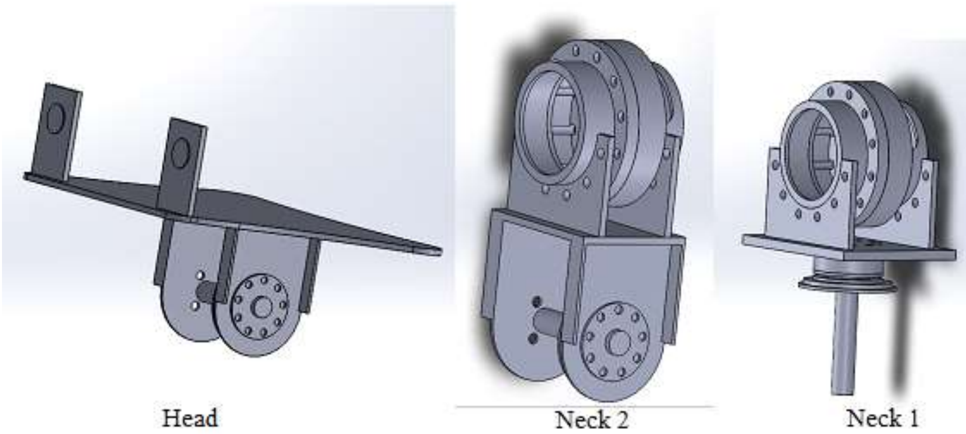


Figure 8-5. Three links build Head/Neck

Also in Fig 8-5 three links of the neck are given, separately also giving the dimensions in detail in Appendix B as well as mass properties in Appendix C. Values of length of links can be read from the dimensions in earlier chapters, from where the values of parameters are obtained; d*1*=103, *a2=58(U8), a3=28+10=38.*

Table 8-2 Denavit – Hartenberg parameters of the Neck/Head

i	***θi***	***di***	***ai***	***αi***
1	Θ1	*d1=103 mm*	0	90
2	*Θ2+90*	*0*	*a2=58 mm*	90
3	*Θ**3***	*0*	*a3=38 mm*	0

From matrix of transformation the following will proceed,

$$ {}^{i-1}_{i}\boldsymbol{T} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_i \\ \sin\theta_i\cos\alpha_i & \cos\theta_i\cos\alpha_i & -\sin\alpha_i & -\sin\alpha_i d_i \\ \sin\theta_i\sin\alpha_i & \cos\theta_i\sin\alpha_i & \cos\alpha_i & \cos\alpha_i d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{14} $$

8.7 Mass properties of Neck (V2)

Coordinate system taken on Joint 1 of Neck/Head, see Fig.8-4. Mass properties of Neck/Head; Mass = 528.33 g, Volume = 167042.95mm^3, Surface area = 83622.86mm^2. Centre of mass (mm): [X = 140.15, Y = 197.07, Z = 174.87]. Moments of inertia($g * mm^2$): taken at the output coordinate system.

Ixx = 38219533.62 Ixy = 14594090.45 Ixz = 12895975.17
Iyx = 14594090.45 Iyy = 28091175.37 Iyz = 18133225.10
Izx = 12895975.17 Izy = 18133225.10 Izz = 31151465.69

8.8 Torque of Arm (joint 3)

Selection of motors is made in accordance with the calculations. When moving the arm it goes from up, down, starting from the frontal level, falling down again in accordance with the plain surface. This raise has the maximum load in actuator no. 2 which is located in the shoulder with this calculation according to the above mentioned formula for angular movement from 0 to 180 degrees of the arm. There is tested the required moment for the actuator to cope with the load. Thus the necessary moment the motor should have to keep the mass of the arm is calculated.

Motor has the maximum load for the angle of 90 degrees, when the arm is kept extended in the front part, parallel to the ground. Three links enter in the arm of the robot and they are marked with the indicators U1 (flange on wrist), U2 (forearm), U (arm). From the calculations of the formulas above, the required power of motors which will be installed on the robot is realised, so that it will afford the mass of hand while moving.

From the above-mentioned formulas, the maximum value of the moment at joint 3 is gained; *Torque*=2.246 Nm that the actuator will have to move in the angle of 180 degrees (Fig 8-6, and Fig 8-7).

The calculations are easy, because there are the dimensions of the links, dimensions of motors and longitudes, and their inertia, which have been given in the respective Appendix.

From values which were have provided in this project, the sufficient torque the motor should have for the movement of the arm is easily calculated. This motor represents the actuator in joint 3 (a Roll movement). The values of this torque have been shown in graph, for the shift for 180 degrees ($\theta_3 = 180^0$) shown in graph (Fig.8-7).

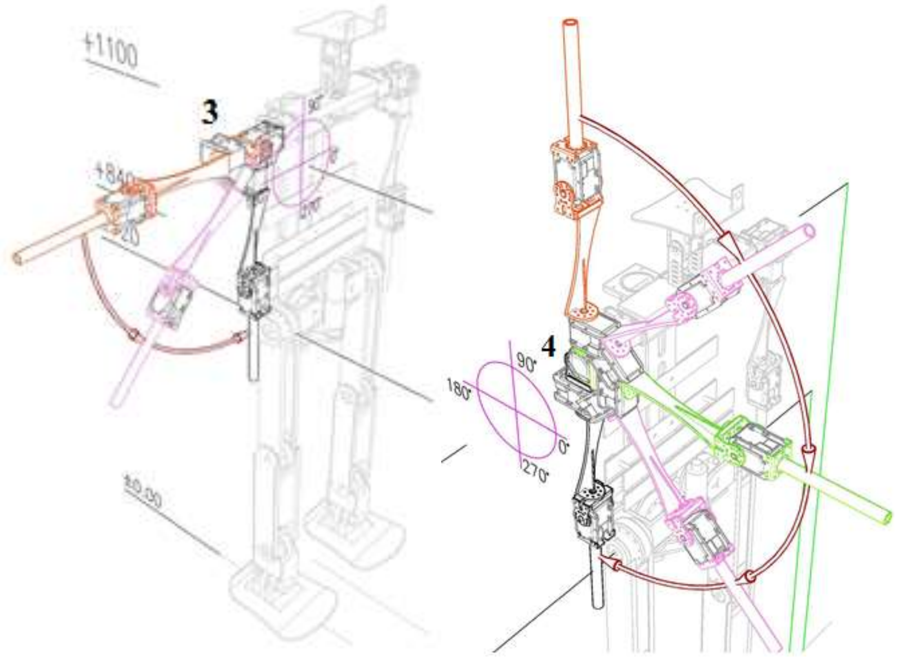
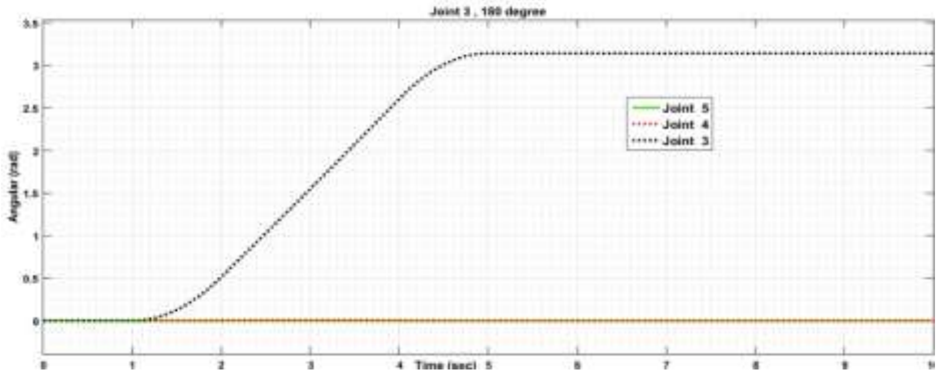


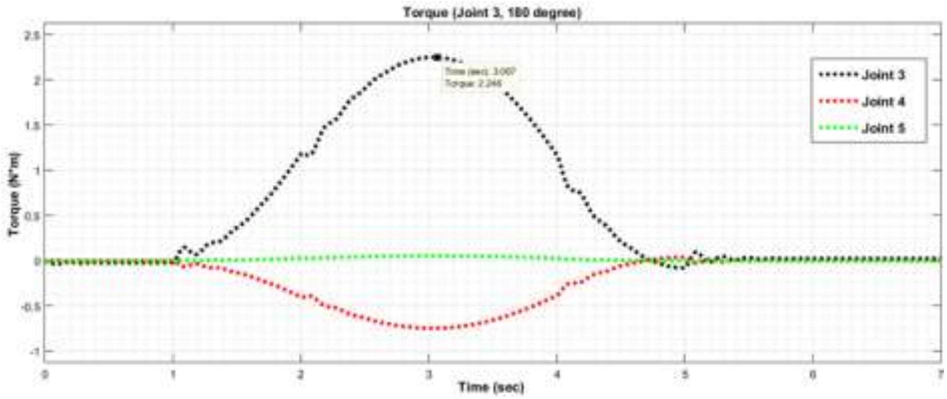
Figure 8-6. Movement of arm

Angular movement is calculated according to the above formulas. Torque is shown in graph (Fig. 8-8) where maximum value of torque is 2.257 Nm. This value is reached for movement of 90 degrees ($\theta_3 = 90^0$), when the arm is horizontal stretching forward.

This calculated value represents the torque the motor will have in the output of the reducer from equation (2).

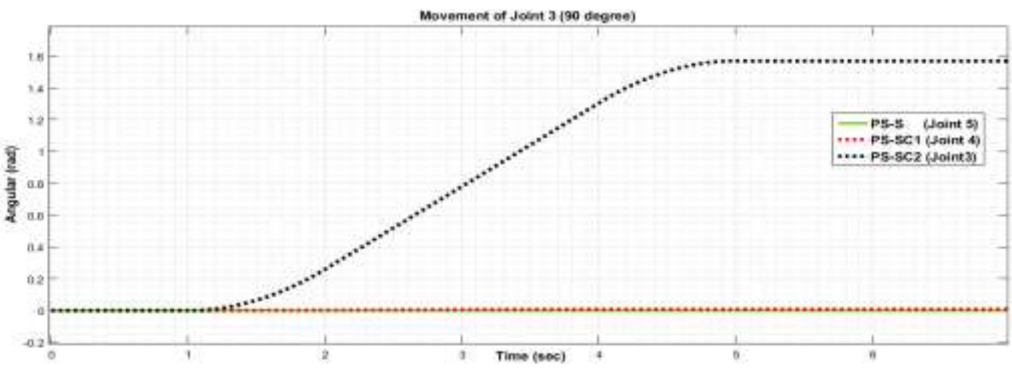


a)

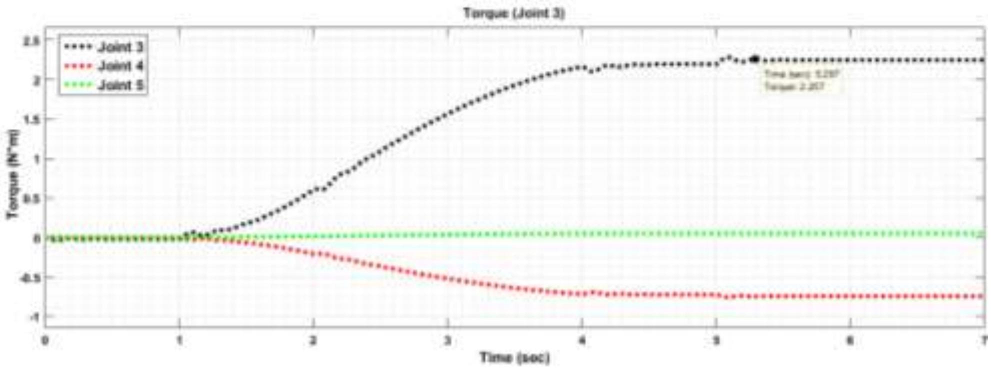


b)

Figure 8-7. *a)* Angular movement and *b)* Torque ($\theta_3 = 180^0$)



a)



b)

Figure 8-8. *a)* Angular movement and *b)* Torque ($\theta_3 = 90^0$)

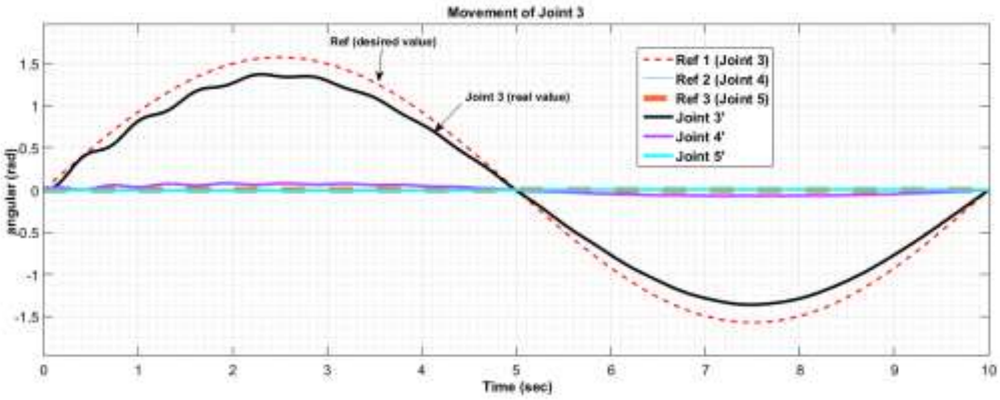
8.9 Torque of arm swing

This movement is made by the arm with motor 3, when the arm moves during walking back and forth, that is a sinusoidal move of the arm. From calculations, the moment M=2.34 Nm is obtained, is given in graph in Fig.8-9. From this value, a brushless DC motor, with power of 50 Watt, having the harmonic drive ratio 1:160, is sufficient to afford a mass twice as much as the mass of the entire robot's arm. Mass of the arm has been given in chapters 6.

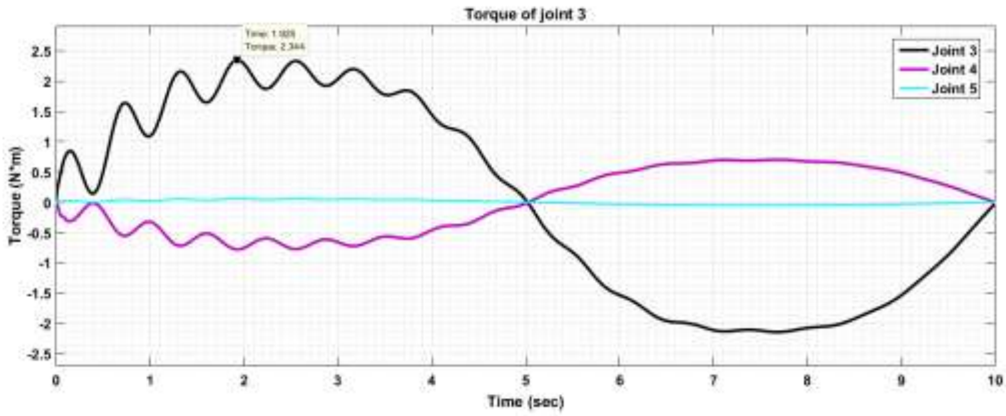
8.10 Selection of motors

Calculating the torque and moment of inertia, in the position of the joint would afford a larger mass during movement of the limbs of the upper part of the robot. The highest mass will fall on the joint where actuator 3 is assembled, which is placed on the shoulder, lifting the arm to 180 degrees raising it from down - up along the frontal plain.

Then holding horizontal position (90 degrees to frontal plain), when the moment of the maximum torque of the motor 3 is approximately 2.3 Nm. In addition, activation of actuator 4, the movement forward-backward happened while walking. While raising the arm aside by activation of joint 3 (Fig.8-6).



a)



b)

Figure 8-9. *a)* Angular and *b)* Torque of joint 3

8.11 Summary

This part provided an explanation of mathematical description of the neck and arm of robot with matrixes of transformation matrix, acquired according to Denavit-Hartenberg convention. The necessary calculations have been made for selecting the needed motors and calculating the torque and moment of inertia.

9 Simulation of design V2

"An experiment is a question which science poses to Nature, and a measurement is the recording of Nature's answer"
Max Planck

9.1 Introduction

This chapter deals with simulation of movement using Matlab 2014b Simulink. Arm movement with joint 5, movement of elbow with joint 4, movement of pitch shoulder with joint 3, helps to see the dynamic features of the arm of robot and the neck, and the possibilities created by the mechanical structure of the design for movement in different angles. This helps to more closely the advantages and characteristics of the design, as during the programming and when performing the movements in real time, it is needed to avoid characteristics that are seen as simulation. Simulation also helps to understand the possibilities of the design, such as movable range, dimensions of the workspace of the end-effectors. At arms, hands, considered as end effector; in this design there is only a flange with a length of 5 *cm*, where the hand structure should be installed.

The purpose was not to make any adjustment; therefore no other type of PID controller has been used. Simulations have been conducted with PID independent in order to obtain rough values of torques the actuators must have. Performance of the movement of designed limbs is also shown.

A list of angular moves and positions of movement is created. Programing trajectories of robot arm, head/neck movement should be avoided. One of important parts, in creating the overall stability of the body of the robot during movement is the part of upper limbs as well. Vibrations in a part of the robot, as is the case of movement of robot arms are transmitted all over its body, affecting the overall stability of the robot. A closer understanding of the dynamic features of upper limb and the possibilities of movement created by design is provided.

9.2 Conditions of arm testing

The design of the robot arm has 5 joints, but taking into account that the joints on the shoulder have a very narrow range of movement, of some degrees, and the movement of the arm back and forth, joint under shoulder remains almost unmovable. For simplification, two joints (1, 2) are not taken into account (Fig. 9-1).

Different cases for each joint are tested, starting from the joints with this order; 5, 4 and 3. In the testing of arm movement, joints 1 and 2 will be considered as fixed in the trunk of the robot for the purpose of simplification of analyses.

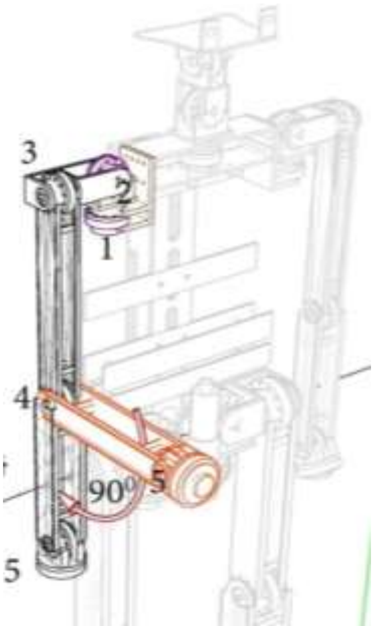


Figure 9-1 View of the right arm, with 5 actuators

The analyses of robot right arm movement have been presented in Fig.9-1, in the second prototype simulations with Simulink tool, in Matlab 2014b. It can be seen in models, displayed in the following figures during the review.

9.3 Clarification on the plot

In chapters 9, 10 and 11, the terms reference values and measured values will be used. The reference values are the expected values whereas the measured values are real value. The physical nature of expected values shall be determined in the unit sent to the joint through PS Simulink Converter, while the output value is taken by giving the real value in respective unit. In each joint there is an input and an output, and such input and output is a couple presented in the graph legend. A couple of curves are also presented in the graph, one is referent or desired, and the other curve is the real value given by the joint.

When system is stable, referent curves of the input cannot be seen, they are covered by the output curves. The values in output are marked only by numbers (3, 4, 5 or joint 3, joint 4, joint 5 or angles; $\theta_{3,}\theta_4, \theta_5$). Always output values are marked at the legend of the plot, as; PS Simulink Converter, PS Simulink Converter1, PS Simulink Converter2, when curves have large differences from the values of curves in input (marked as Constant, Constant1, and Sine Wave) it shows lack of stability at movement of arm. The smaller are differences between output and input value the more stable are the movements.

9.4 Simulink Application

All the information for Simulink has been taken from help of Matlab 2014b, and from the official web page of the company that sells this product.

Simulink Library contains the blocks, bodies and joints, equipped with sufficient blocks can build the model, so that it can make arm movement, simulating robot arm movement. In simulations, during testing, gravitation and mass of the reviewed part are taken into account. The model also gives the world coordinates, mechanical configuration sets, where mechanical parameters have an impact on all parts of the robot, taken in consideration for the simulation. Gravity is calculated in this block, and linearization delta shows calculations, values of perturbation during movement of robot hand, when using the numerical derivatives for linearization (see in Fig 9-2).

The robot is connected to port C at the block with F port at robot's arm that means that it is connected to the fixed joint of the shoulder that is fixed at robot's body, marked with joint 2. On the other side of this link, the joint 3 is located as presented in the following figure. This represents the revolute joint between two systems of coordinates, and the connection between the two links, build from the shoulder of the robot.

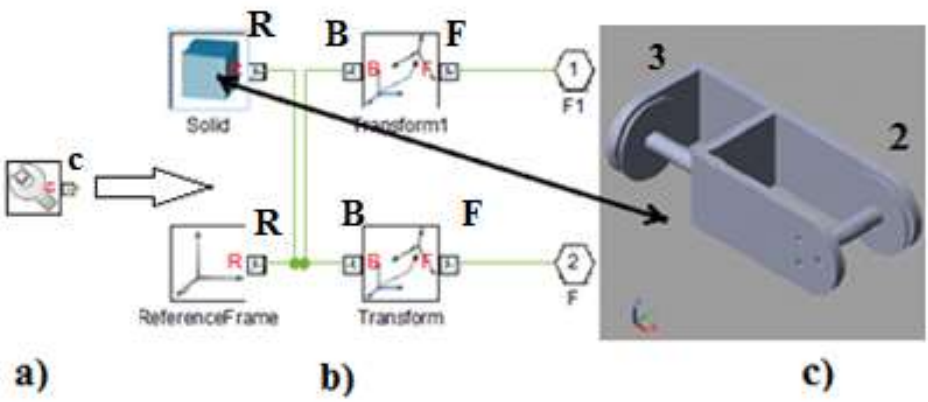


Figure 9-2. Simulink block diagram

The image of the icon is given for the block called World coordinate, Mechanical configuration Sets under a), while under b) Internal construction, whereas under c) is the view of the shoulder of the robot where joint 2 of the design is located. That point is considered as the place where the right arm is attached. Then, within the block of World coordinate, Mechanical configuration sets, there are transformation coordinates, reference frame, and the view of the link part is provided, and connected with joint 2 on the one hand, and with joint 3 on the other side.

The figure (Fig.9-2) provides Transform1 - Coordinate system of joint 3 and Transform - System of coordinates of joint 2, the link with Reference Frame is located between joint 3 and 2. Joint 1 represents the motor, located under the shoulder, and narrower range of movement on robot upper body.

The robot arm is fixed at point 2. In all models, Simulink PS-Converter sends to the joint the expected value in a certain torque with units Nm, thus simulating a torque in respective joints, marked by 5, 4 and 3.The output value of the position (real value or measured value) of the joint move, while PS-Simulink Converter gives the unit to that radian or degree of shift value.

9.5 Test 1 (joint 5)

Upon activation of actuator of the joint 5, the hand movement takes place. Normally hand can move at different angles, but the maximum angle is 180 (+/- 90). When explaining that a joint moves 90 degrees, it means that this movement occurs in reference to frontal surface (+90) on one side, and (-90) on the other side of the frontal surface. The robot is on foot, taking the frontal surface as initial position, any movement of joints on one or to the other side of plans are marked by '-' or '+' (on the same or opposite direction of clock indicators, starting from frontal plan). If the reference value is the rotating moment (torque) values are repeated according to sinusoid, regulating joint 5 rotation (with angle, +/- 90), only through proportional controller, while the joints 4 and 3 are static. The PID controller values: [(10, 10, 10) (0, 0, 0,) (0, 0, 0)]. Model for the movement of the joint 5 is in Fig. 9-3. Expected values of Joints (3-contstant value, 4-const=0, 5-Sine Wave (90 degree)).

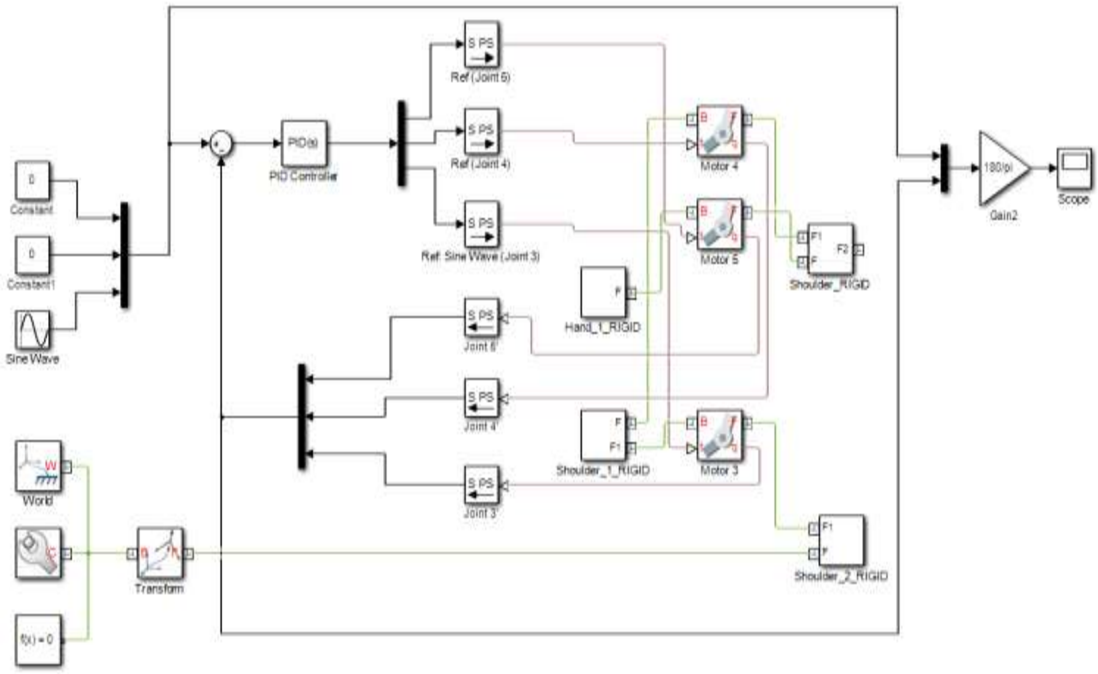
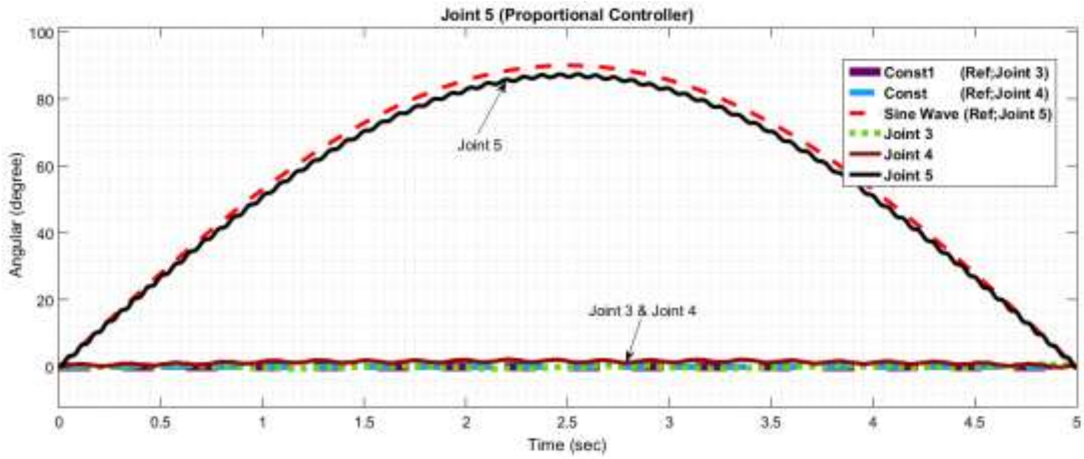


Figure 9-3. The model for arm movement in joint 5

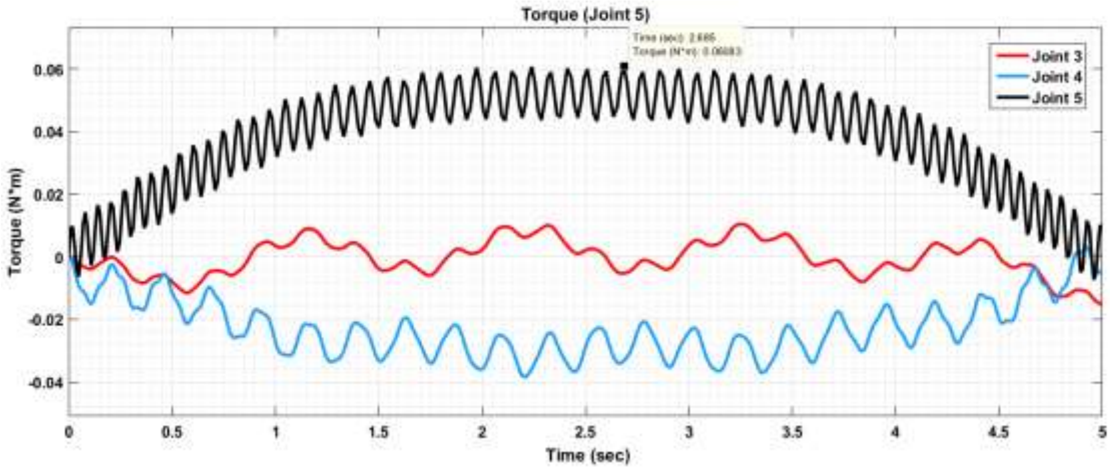
Vibrations are of low amplitude and torque. Joint 5 move the link and it does not cause much vibration to the arm. The torque (0.0 6 Nm, in Fig 9-4, under *b*) is not high because of the short link of wrist, and after using after using derivative controller, the torque drops down from 0.06 till 0.053 Nm on Fig 9-5 (under *b*).

Vibrations are not so significant, because the link connected with joint 5 (wrist), has a short length (5 cm), so the moment of force in wrist is short. Hence, in longer distance from joint 3, the shakes are stronger.

The adjustment with the PID Controller [(10,10,10) (0,0,0,) (1,1,1)] at the three joints of the arm has ceased almost completely all the vibrations, and all curves on the plots are overlapped with values at the input, and they are smooth.



a)



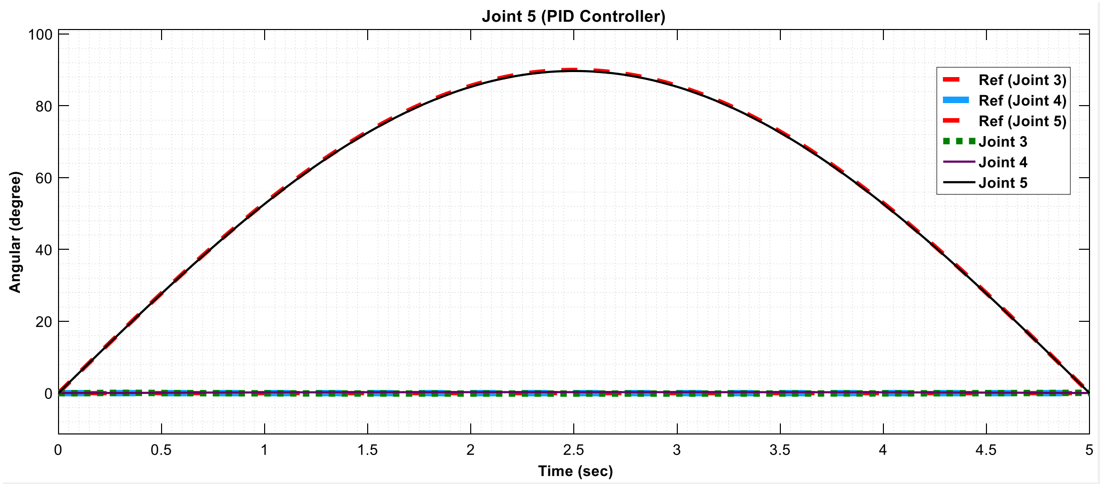
b)

Figure 9-4. *a)* Movement of joint 5 and *b)* Torque

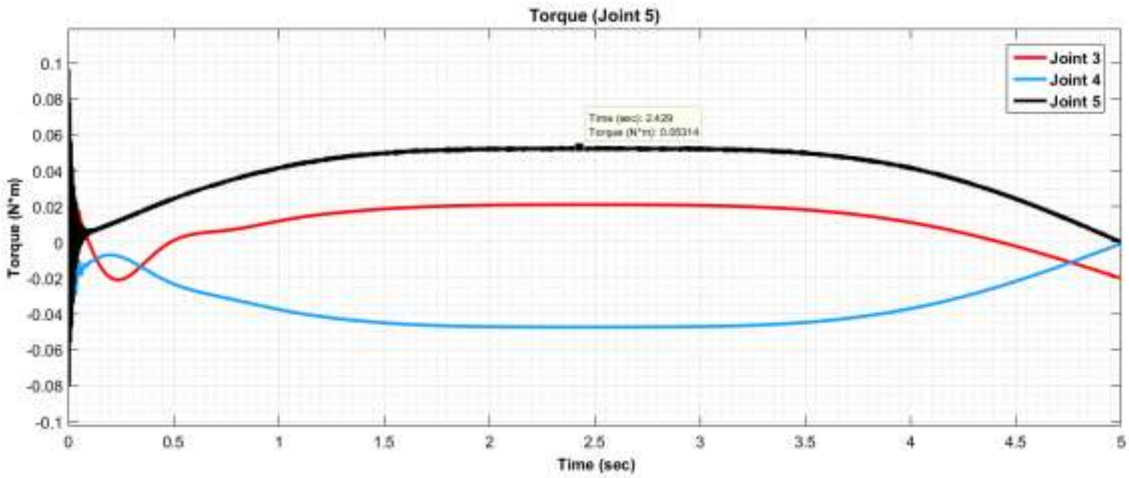
Vibrations of the joints will almost disappear, by improving the movement of the arm, the movement is conducted without vibrations that can be seen on the graph in Fig.9-5.

Any kind of vibration in joints causes undesired vibrations to the nearest joint, affected by each other; this can be seen from the reduction of vibration in joints; 3 and 4.

The cause of vibration of the whole arm, with movement of wrist, occurs from the moment of the force of oscillations, as it grows going from joint 3 in direction of joint 5.



a)



b)

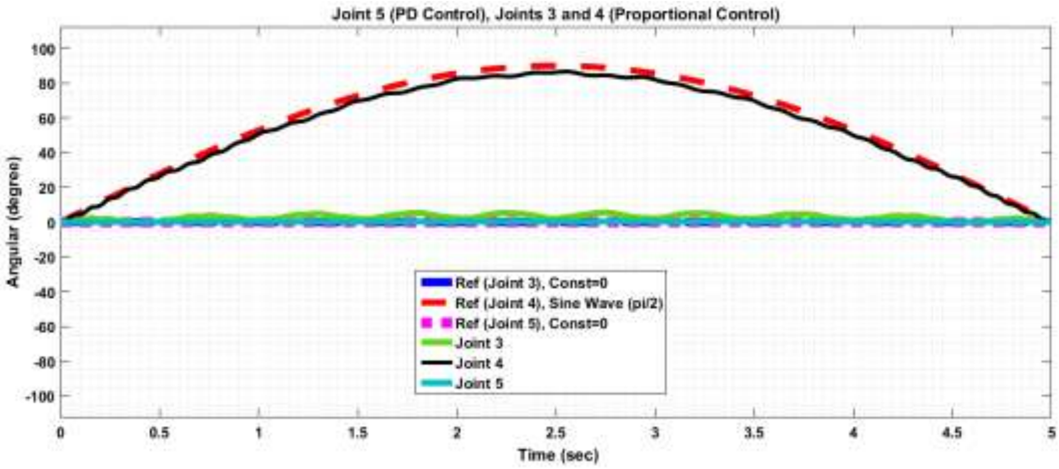
Figure 9-5. *a)* Movement of Joint 5 and *b)* Torque with PID

9.5.1 Conclusion on test 1

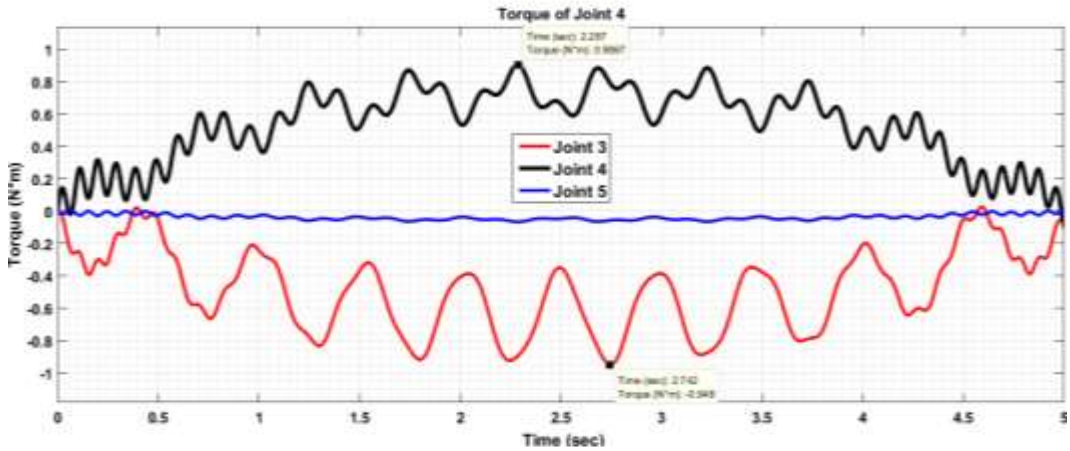
By comparing the plots in Fig.9-4 and Fig.9-5 (under *a* angular movement and under *b* torque), the impact of the derivative part of PID controller can be seen, for removing overshooting, and smoothing the waving in the graph that represent the low vibrations and low torque in joint 5. PD controller should be implemented in the joint when movement takes place, but upon further improvements, PD should be used in all joints. Joint 5 is located at the end of the arm has a moveable range for the angle (180^o) +/-90^o.

9.6 Test 2 (joint 4)

Case 1- In joint 4 it is a sinusoidal reference value with amplitude$\pi/2$, regulated only with Proportional Controller. PID Controller with the following values; PID[(10,10,10), (0,0,0)), (0,0,1)]. The model is the same with the model of movement of the joint 5, with a difference that the block (Sine Wave in model) operates with rotating moment with sinusoidal values in joint 4. In the two other joints, the constant zero values are sent, holding the rotating joint in 'frozen' position. In case 1, the maximum torque the motor should provide continuously is 0.9 Nm, in (Fig 9-6) under b).



a)



b)

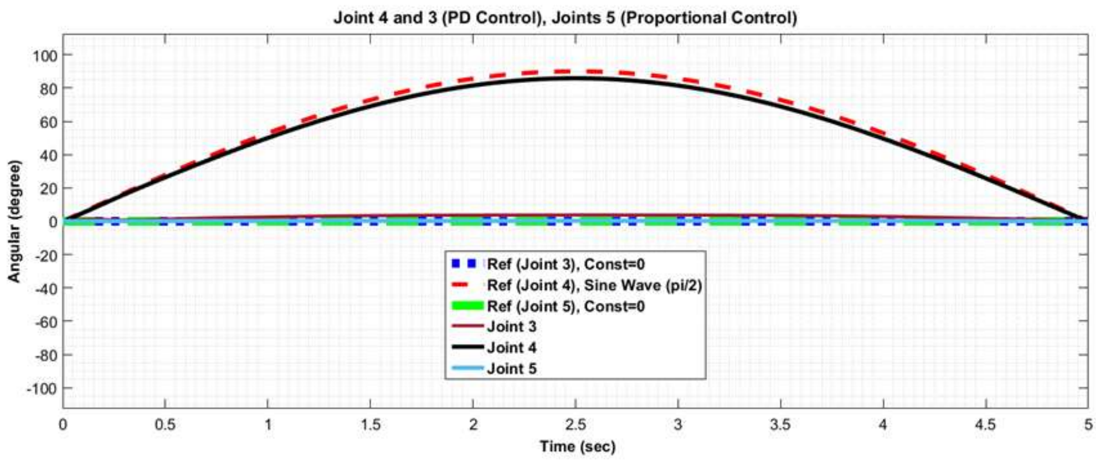
Figure 9-6. Plots with PID in joint 5

Arm moves is adjusted by proportional control approach in the three joints: 5, 4 and 3, while with proportional and derivative for the joint 5 (wrist). During the movement of joint 4, for the angle **+/- 90**, movement of arm is associated with small vibrations. Stability in joint 5 can be seen at the plot; curves with the purple and blue colours cover each other, while waves of joint 3 are caused by movement of joint 4 (Fig. 9-6). This movement followed by periodic vibrations of the entire arm is not permitted for the robot.

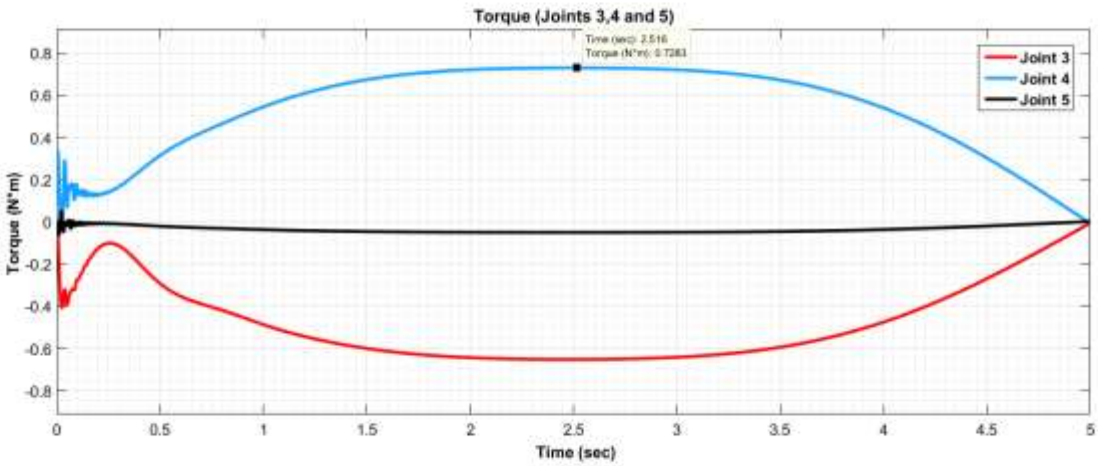
During the implementation of this movement, vibrations will occur all over the body of the robot.

Case 2- PID controller adjusted, with the PD controller in joint 4, while only Proportional controller is applied in joint 3 and 5 (the joint where rotation takes place, with the torque). PID Controller has the following values; PID[(10,10,10), (0,0,0)), (1,1,0)];. Block with the module Simulink **Sine Wave** creates torques with amplitude$\pi/2$, with the movement of the arm on elbow for +/- 90 degrees.

From the graph in Fig. 9-7, it is shown that in a short time interval vibration suppression begins in joint 3, presented with the blue curve, also vibrations in joint 4 fade out completely in the second half of the period. This movement is allowed at robot arm. The torque will be 0.7283 Nm, (Fig. 9-7).



a)



b)

Figure 9-7. *a)* Movement of Joint 4 and 3 and *b)* torque

9.6.1 Conclusion on test 2

From this test it is concluded that the part of Derivative Controller stops the vibrations, especially at the transitory time, when it starts moving, it prevents overshooting. If a Derivative Controller is installed at every joint, movement of the arm improves to maximum.

9.7 Test 3

In the case of movement, the joint 4, forms 60^o angle; forearm and arm that are connected in joint 4 form the angle of 90^o. Forearm is moved before starting the movement to the frontal plane in perpendicular way as in the Fig. 8-10, position numbers 1. While all the limbs and the body trunk of the robot lies in the frontal plan. This position has been called the asymmetry of hand to other parts of the body. Asymmetry of robot position at the beginning of movement generates vibrations and instability during an interval as a consequence of the action of gravitational force with the same direction of action of the torque (Fig.9-1).

Vibrations affect the entire joint of the arm, in a transitional process to stabilize from time T1=0 until T5=2.598833 when vibrations stop values can be read in the plot Fig.9-10.

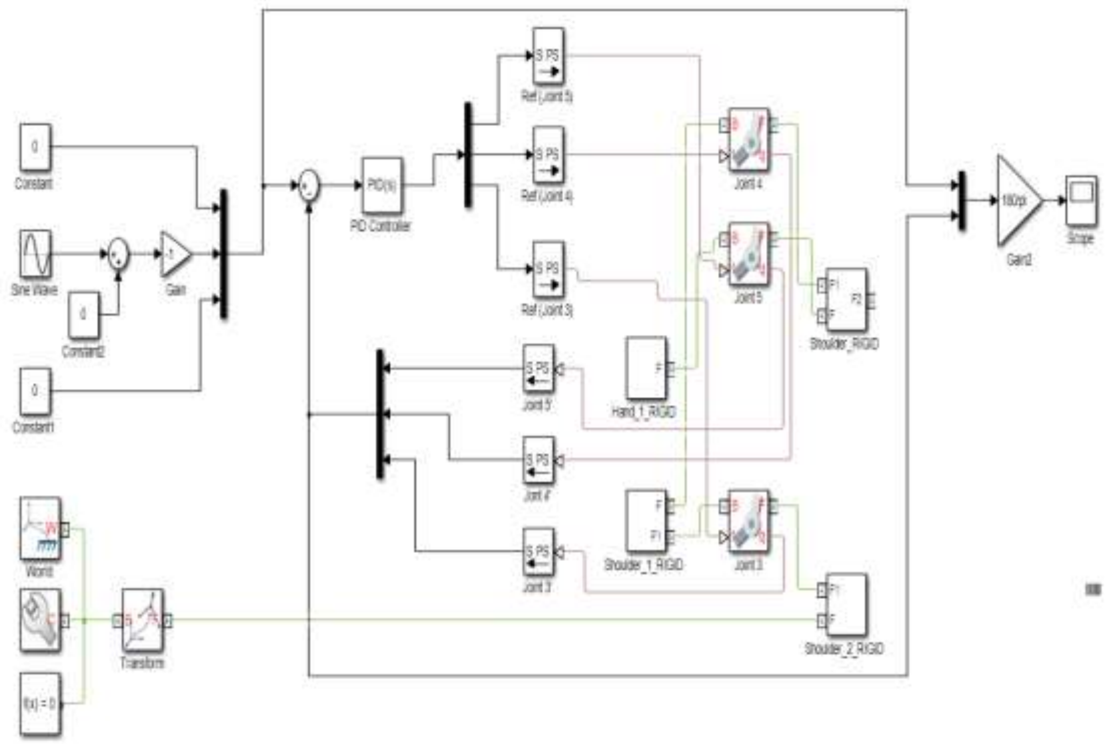


Figure 9-8. Model presented in Simulink, movement of joint 4 (rad$\boldsymbol{\pi/3}$).

The model with blocks Sine wave that generates sinusoidal signal operates in joint 4.Constant block holds the joint in the condition presented in Fig.9-7, and gains value -1, when elbow is flexed to 90^0, and from this position to start with sinusoidal shifting for 60^0, in direction of frontal plan.

The plot presents the interval from 0-5 seconds while in interval [0-0.056742] when major vibrations take place on the arm of the robot marked with numbers, images from 1 to 5, in Fig.9-9. The numbers provide the images of vibration and the time when they occur can be seen in the waves of curves in graph in Fig. 9-10, under *a)*.

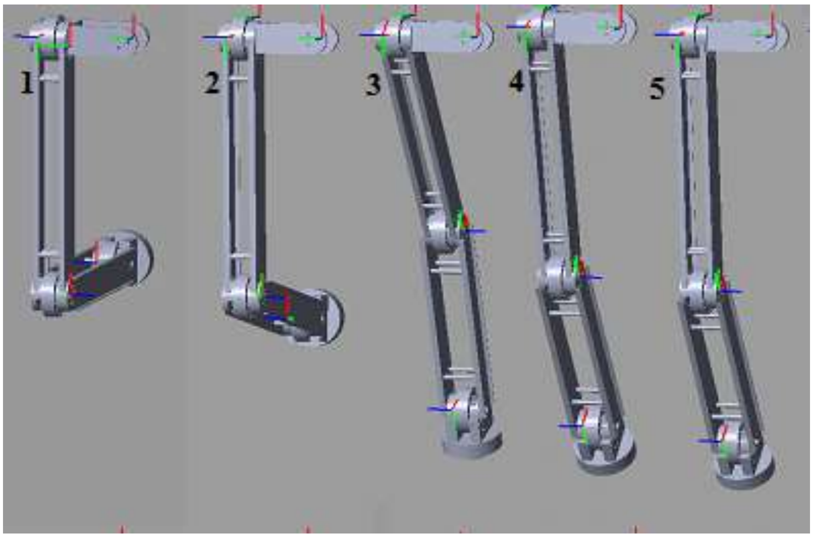
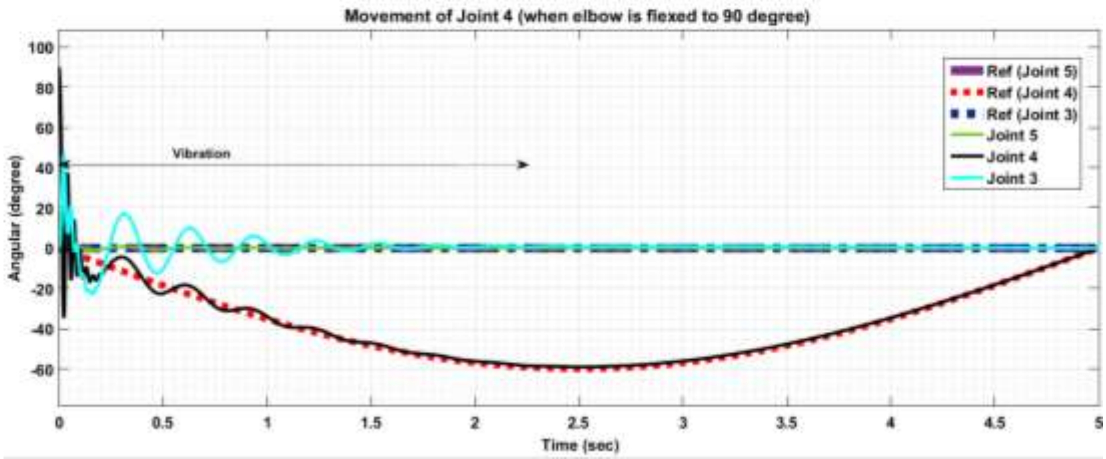


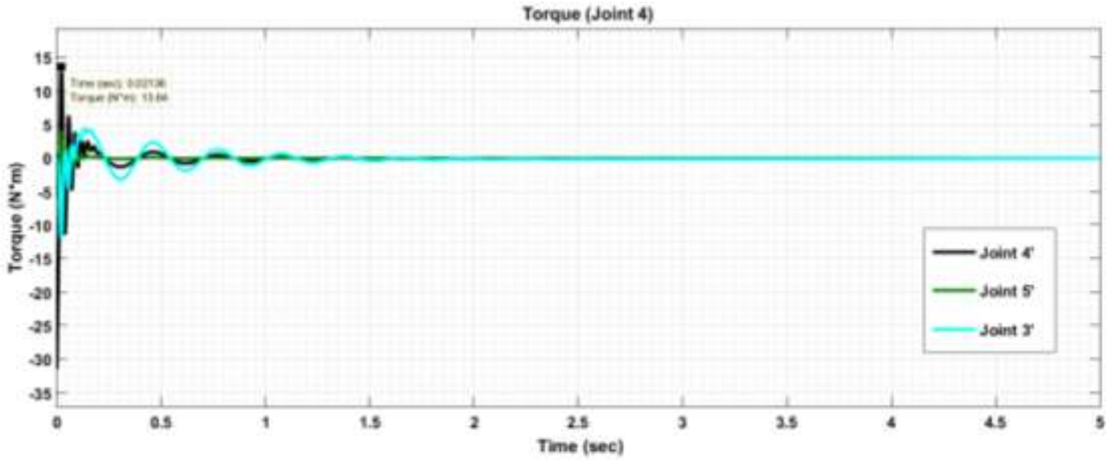
Figure 9-9. The right arm at moment of movement.

A position of the static hand (movement starts from this position number 1 in Fig 8-8, in asymmetry to movement of 90 degrees from frontal plan (Fig 9-1). These oscillations affect all body of the robot and should be avoided; this is the worst case of the start of movement. Arm one following a transitory period, begins to stabilize, approximately at time *t=2.53s*, a value that shows removal of waves from the mechanical structure of robot, as it can be seen in the plot presented in Fig.9-9. Images of positions of the arm have been shown by numbers at the respective time on the graph. The images of shakes to the moment have been presented.

From this, vibrations are read at the beginning of the movement of the joint 4 (elbow), as a consequence of the gravitational force added with the torque that operates in joint 4. This affects the powerful shakes of joint 3, supposed to be in normal conditions with a straight line according to the referent curve in graph. With the removal of the derivatives, leaving only PI (proportional integral) controller, arm movement becomes unstable and unfeasible.



a)



b)

Figure 9-10. Asymmetry of forearm, *a)* movement and *b)* torque

9.7.1 Conclusion on test 3

From test 3) it is concluded that the movement of limbs, when one of the limbs has asymmetry in large angles by frontal or sagittal plane, as in the case of 90^0, must not start with the movement of the robot. Even if it happens to have large angles of displacement toward frontal plane or on one side to the sagittal plane, the movement starts with small angular moves. This problem can be avoided with computed control torque; acting at the beginning with the small moments of force and low speed.

9.8 Test 4 (joint 3)

Movement of the joint 3 shall be regulated with the PD controller; torque operates in joint with values that are repeated in the sinusoidal value of $\pi/2$, while joints 5 and 4 are regulated only with proportional, a constant signal keeping joints (joint 4, joint 5) immobile. Model (as shown in Fig. 8-3) is the same as the model for the movement of joint 5, with a difference that block Sine wave is connected with joint 3, so that the constant blocks are related with joint 4 and 5. Movement of the joint in practice will be accomplished by moving the rotating shaft of actuator, which is going to be placed in the respective joint.

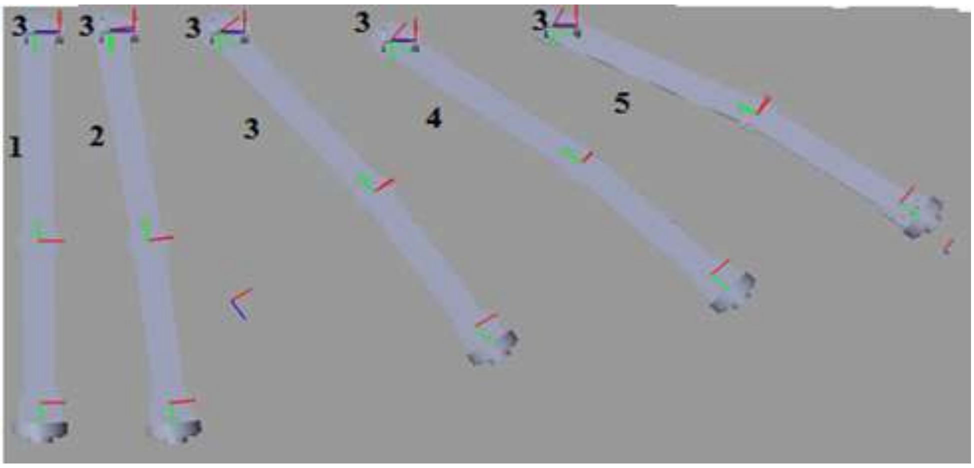
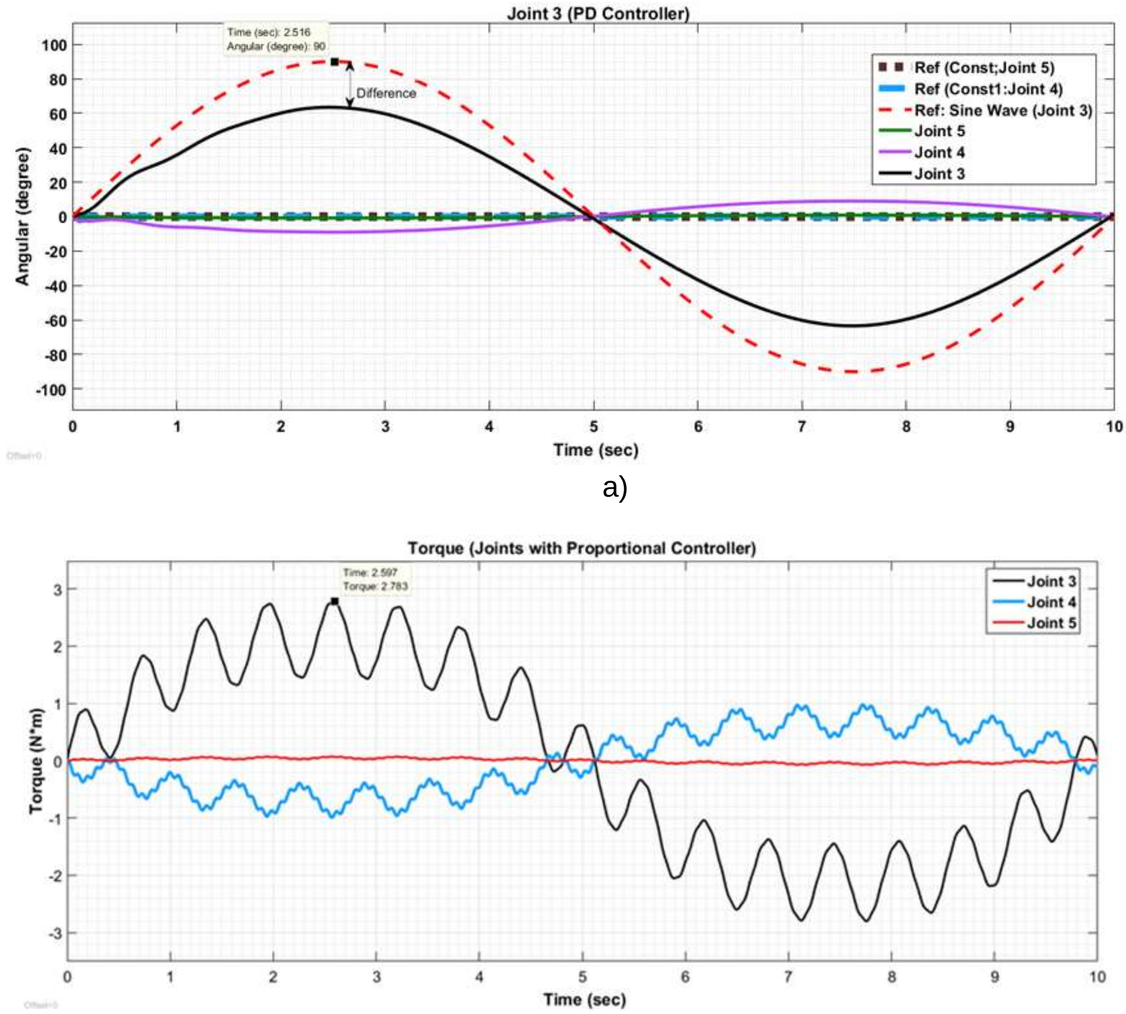


Figure 9-11. The movement of joint 3

The figure contains images of positions of the arm for five moments during the movement for 90^0 degrees. The arm moves with rotation only at the joint 3, while joints 4 and 5 are still. The movement of arm at moment (Fig 9-11) bending elbow (at joint 4) are taken from simulation. In the graph in Fig.9-12**,** in legend there is a sinewave (Joint 3), it represents the reference value which has the sinusoid value, while the other value at output marked as measured value (Joint 3). In graph it can be seen that the two signals have the shape of sinusoid with great distance from each other. This comes from the shift of joint 4 that bends the arm and should be immobile. This bending provides a shifting of the output value for the joint 4 (the curve with purple colour), it can be seen in the plot. In fact the curve of the joint 4, as if the movement were stable without any vibrations, the curve must have been a straight one because it is with zero amplitude.

Sinusoidal movement of joint 3 *does not have the amplitude that it should have had as seen in Fig.9-12 (under a)*, and the torque is 2, 78 Nm (*Fig.9-12, under a)*, where the arm of the robot has taken the shape of the bow, with small angular shift in joint 4.



a)

b)

Figure 9-12. Joint 3 with PD controller (*a*-movement, *b* torque)

9.9 Test 5

Improvement of movement in test 4) is done by changing the values in PID controller, PID [(1,1,1),(0,0,0), (0.1,0.1,01)] to PID[(10,10,10),(0,0,0),(1,1,1)], vibrations being fully reduced, and the arm moves without bending in joint 4.

Vibrations of the joint 4, in the graphic in Fig. 9-12 have been fully eliminated in Fig 9-14. There is no bending in joint 4 as seen in Fig.9-11. This image of arm movement has been taken from the video, simulating movement of the design.

In Fig.9-14, we see that all curves of the plot are almost covered by one another. The values of Ref (Joint 3- the referent value) are at the input of the joint, they almost match with output values of the Joint 3.

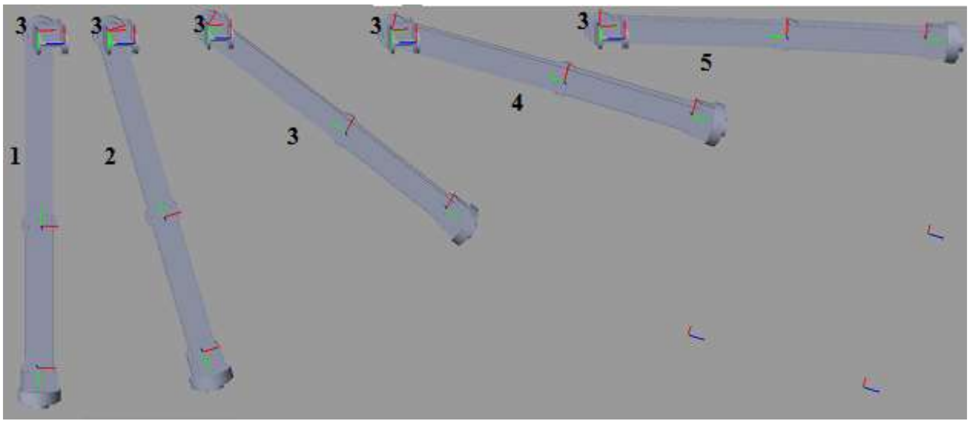


Figure 9-13. Image of the arm movement

The two curves have no differences and the curves are smooth (Fig. 9-14), this shows for a stable movement of robot arm (Fig.9-13).

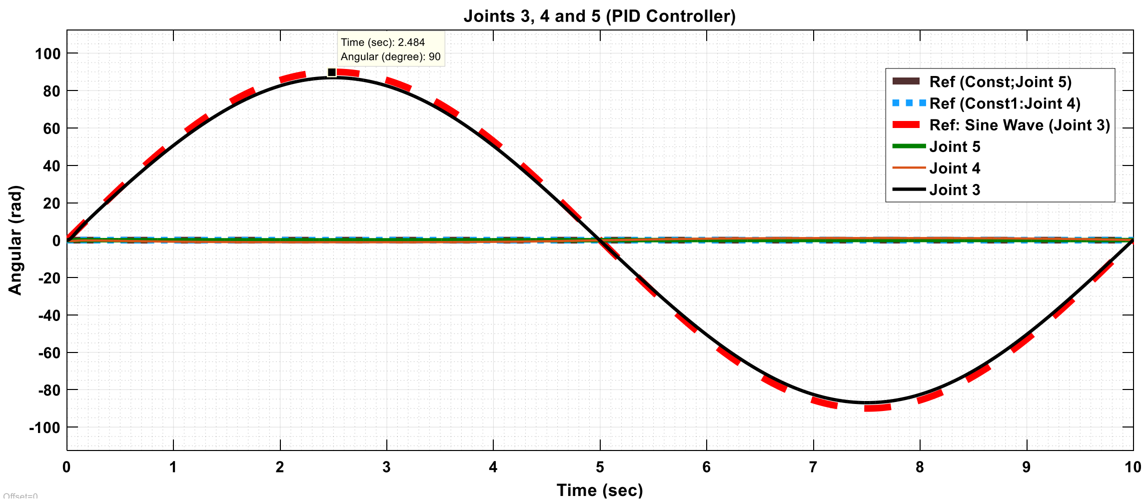


Figure 9-14. Plot shows the move in joint 3

9.9.1 Conclusion on test 4 and 5

In Fig 9-13 and 9-14, curves in the graph, almost all of them match with each other, from this, the arm movement is stable without vibrations. Through PID Controller, for every joint, the arm is kept still in joint 4, facing the mass of links during movement of the arm, and other dynamic values expressed during movement of the arm. Movement is realized with angular displacement in joint 3, with sinusoidal torque with amplitude$\pi/2$. Coping with weight during the movement of the arm, PID Controller can compensate the mass of the part of the arm from joint 3 to the part where the arm of robot is assembled.

10 Testing of Head/Neck (V2)

"Knowing is not enough; we must apply. Willing is not enough; we must do"
Johann Wolfgang von Goethe

10.1 Introduction

This chapter provides mechanical analysis of design of the robot, of its upper part, respectively neck. The neck movement will be seen, where there is no particular risk for robot stability. Tests of the neck show possibilities that the design gives in orientation of cameras, and the possibilities of movement in different trajectories, so that it orientates in different angles. Movement of head, to follow obstacle objects by sight, refers to trajectories and angles as it can direct cameras through 3 DOF of the neck, shown in Fig 10-1. There are provided different cases of movement of joints, for various values of angular movement of neck/head. In our case as end-effector are cameras at the kinematics chains of links with three joints of Head/Neck.

10.2 Software used for simulation

A simulation refers to behaviour of mechanical structure of design, through graphs obtained through SimMechanics tool. Design of the robot has been prepared in AutoCad, while this design has been imported in SolidWorks and from SolidWorks it has been imported to Matlab. With Simulink and SimMechanics the model is created by simulation, on the behaviour of robot arms.

The necessary changes in SolidWorks were made, joining parts of design in one group which forms the link, putting points where the movement occurs, that is also the point of union of two links of the mechanical structure. At the joints, it should always be understood that an actuator is there to enable the move. Furthermore, from SolidWorks 2016 it is imported to SimMechanics in Matlab 2014, from where the structure in block diagram is generated. In the Simulink library, there are blocks given from the model. From blocks, a certain model has been built in order to create the desired movement of the arm and neck/head of the robot. The graph shows values that describe the mechanical behaviour of the structure of Archie design, movement of the arm and neck/head. Serial structure of the neck/head consists of three rotating actuators in an order by 1, 2, and 3**.** They are presented below.

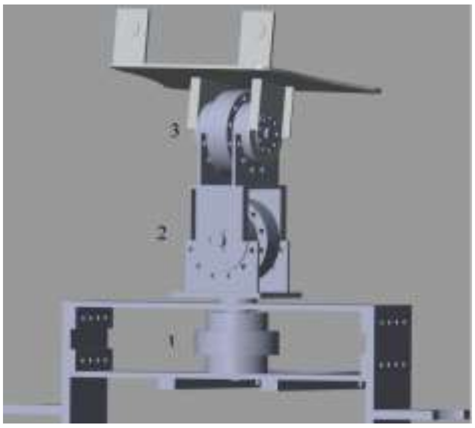


Figure 10-1. Neck/Head V2

10.3 Test 1

In test 1) and 2) PID Controller has the following values; PID [(10, 10, 10),(0,0,0) (0.1, 0.1, 0.1)]. The model (test 1) consists of 12 ramp blocks (Fig 10-2). The objective of this example is to show the possibilities created in combination of joints, to direct cameras in sight of the object in motion, when it makes a movement in a rectangular form. With *pan* movement of joint 1, and pitch movement of joint 3, while joint 2 that makes *roll* movement is immobile.

The table (Tab.10-1) provides the values of Ramp signal, generating a signal in a straight line shape with a respective slope of certain angles. Signal means a value of the rotating moment in the respective joint. The straight lines mathematically are added from side to side, gaining a resultant trajectory, from point to point (as an example from the moment 0 to moment 1, there is a Ramp = (- $\pi/2$,)/1, while at the same interval, Ramp 6 = 0. From Ramp+Ramp6 = (- $\pi/2$)/1, with this interval (0 to 1) joint 1 of neck will make a movement for angle of 90° in direction of clock indicators illustrated with figures given in Fig.9-4., and so on gaining the curve for actuator 1 (for movement of the joint 1, for angle θ1 and actuator 3 (for angular movement θ3) as shown in the graph presented in Fig.9-3.

Combination of movement of both joints 1 and 3, being static joint 2, movement of cameras is obtained, (and the movement of the head) in a rectangular trajectory. This case also shows the possibilities of the designed neck, for the cameras to look to the sides, and forward to under different angles. Adding of two curves provides the rectangle shape of head movement. Curve in green colour represents the movement of the joint 1, while the one in blue represents joint 3. Fig 10-3 shows at the edges the waves appearing to grow. Waves are of low amplitude; in practice are small vibrations of the head of the robot when the actuator started to move. The vibrations are undetectable.

Curve waves are caused from the moments of rotation of joints 1 and 3, thus withstanding the mass of the neck/head to begin with movement (Fig.10-3).

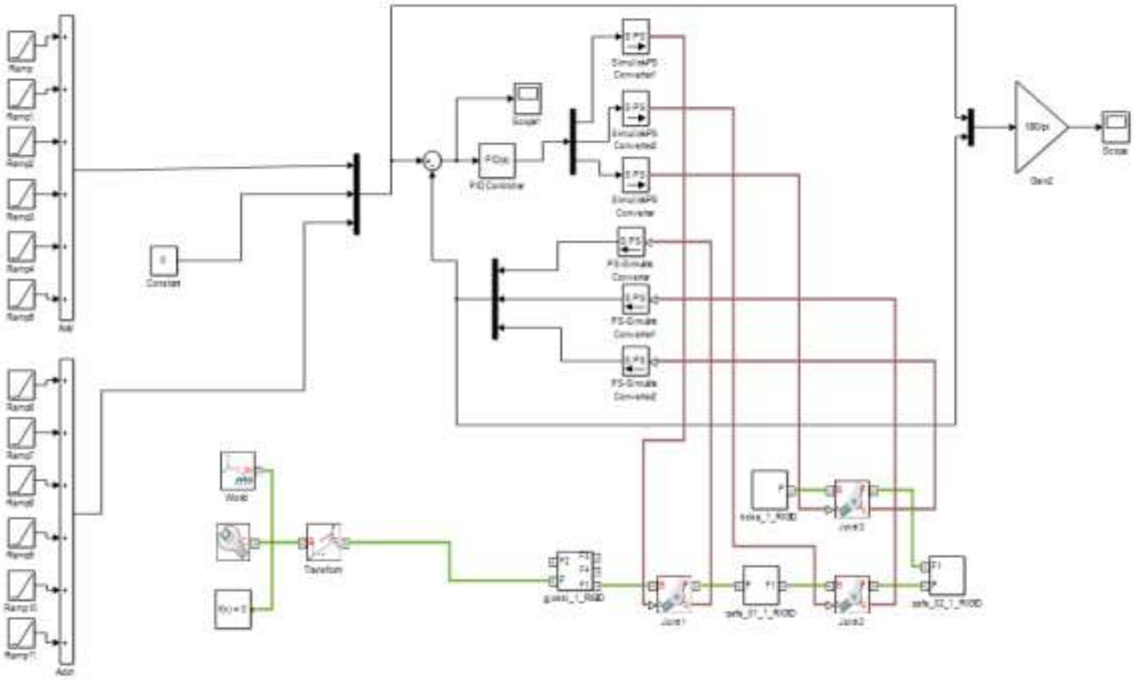


Figure 10-2 A model given in Simulink with Ramp signal

First it begins with movement of joint 1, for$\theta_1 = 90^0$, a shift caused by the motor stands in the position between the shoulders creating pan movement (left-right), orientating head and by this the cameras too. The joint 3 moves for the angle of 30 degrees, directing cameras bottom-up.

Numbers of photos in Fig.10-5, are positions of the head of the robot presented in figure, during movement, they present moments of time, such as; *T_0=0, T_1=1, T_2=2, T_3=3, T_4=4, T_5=5 and T_6=6* have been marked at the axis of time in graph in the figure (Fig. 10-3).

Moments T1 (moments of the beginning of movement) and T6 (moments of the end of movement), are equal by value, but occur in different times, but the position of the head is the same.

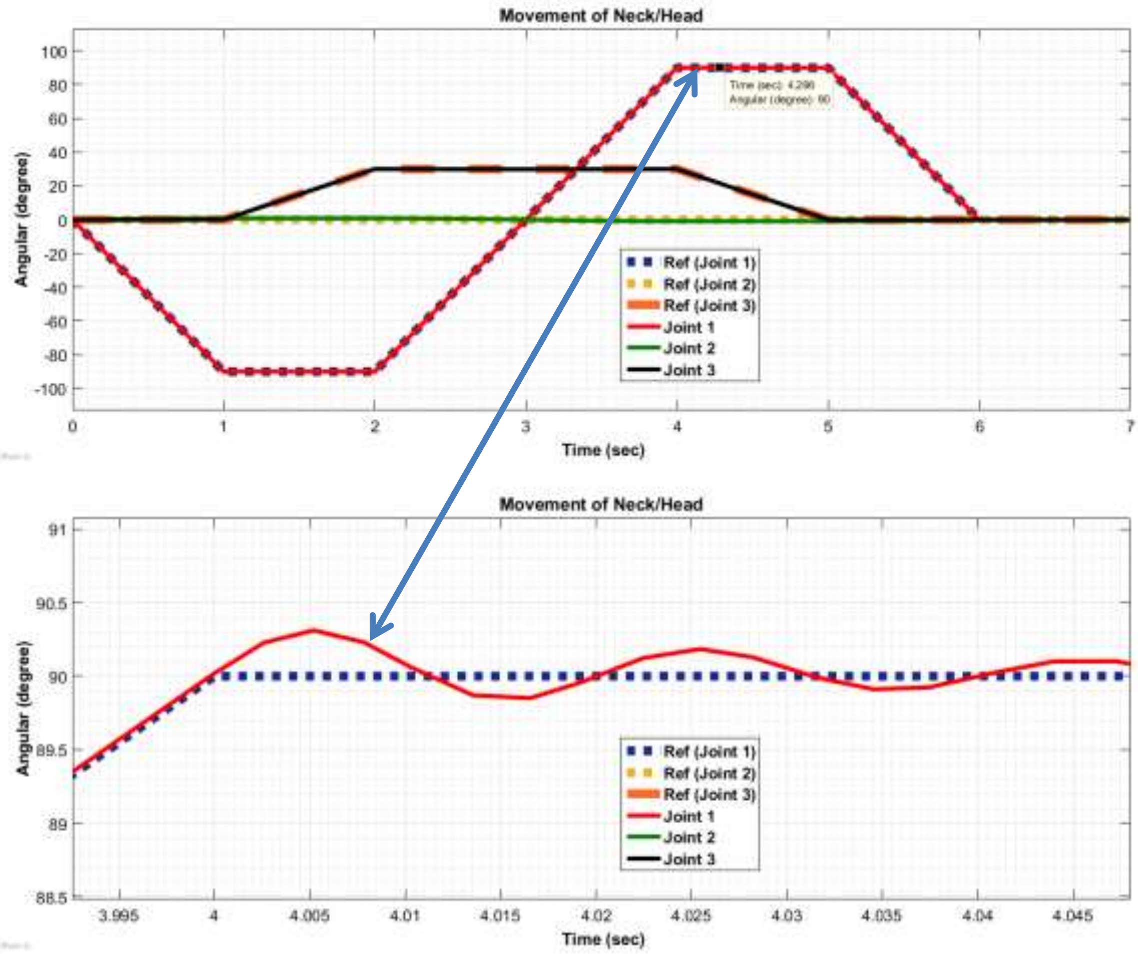


Figure 10-3. The joint 1 and 3

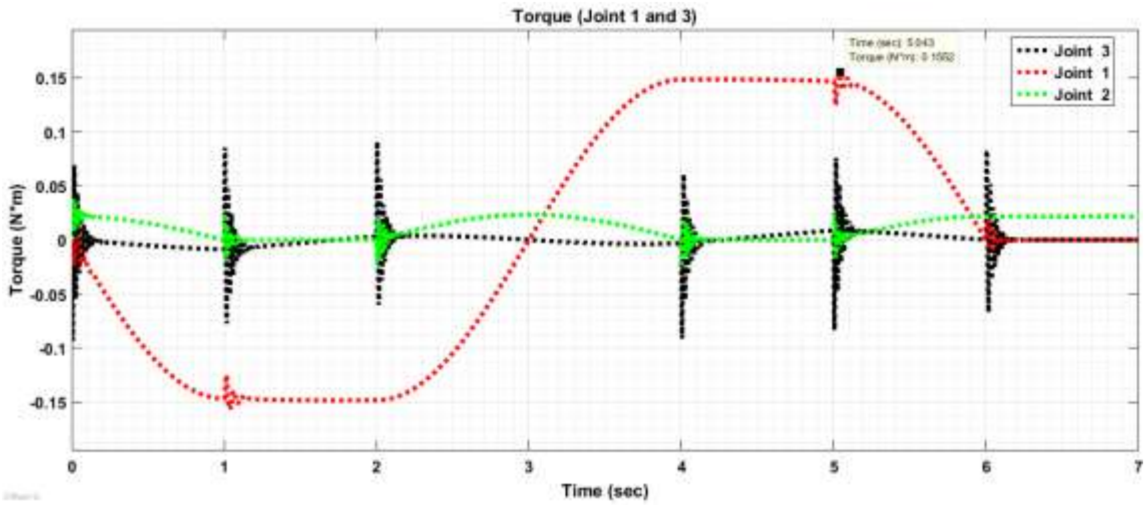


Figure 10-4. Torque of joints 1 and 3

Example in T=3sec, the head has the position as in Fig.10-5, with number 3, so every number in photo represents the time, the positions can be followed by the time line in the graph in Fig 10-3. The maximal torque for joint 1 is 0.15 Nm (Fig 10-4).

Table 10-1. Values of the signals

Signal	**Slope**	**Start time**	
Ramp	$(-\pi/2)/1$	**0**	**Joint 3**
Ramp1	$(\pi/2)/1$	**1**	
Ramp2	$(\pi/2)/1$	**2**	
Ramp3	$(-\pi/2)/1$	**4**	
Ramp4	$(-\pi/2)/1$	**5**	
Ramp5	$(\pi/2)/1$	**6**	
Constant value	0		**Joint 2**
Ramp6	0	**0**	**Joint 1**
Ramp7	$(\pi/6)/1$	**1**	
Ramp8	$(-\pi/6)/1$	**2**	
Ramp9	$(-\pi/6)/1$	**4**	
Ramp10	$(\pi/6)/1$	**5**	
Ramp11	0	**6**	

The head will make a sinusoidal move permeating through cameras objectives of a wide range of observation, without stopping the move, and without vibrations, and it will be discussed below, in test 2.

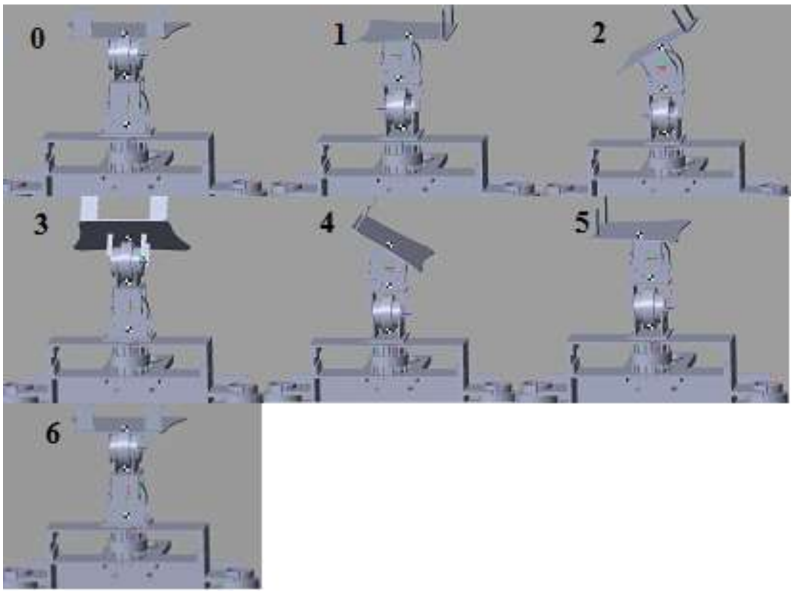


Figure 10-5. Movement of the head

10.3.1 Conclusion on test 1

Movement of the head directs the 'look' of cameras in a rectangular trajectory, being stable and feasible. This example shows the advantages of design, and a sufficient number of joints, respectively actuators. Cameras go through quite a broad workspace and sufficient for detection of objects, from any position where they are located in relation to the body of the robot taking distance of 3 to 5 cm from the body of the robot. Cameras can be sufficiently directed to any position, starting from the frontal plane and on the entire parallel space with this plane. The robot can follow by "looking" the objects in motion as well. Distance of sight is limited by technical features of cameras.

When the design of the head/neck provides sufficient possibilities of cameras for them, they turn into directions and angles, as it is more suitable to investigate (observe) objects, or to follow the trajectory that the robot will go through. Also, with this move of the neck/head, it can follow through cameras, an object in motion on a broad table, or on the floor to see its square space as to find the objects the robot was ordered to detect.

10.4 Test 2

The same move in test 2), but with a sinusoidal signal that in fact represent moments of force that operates in rotary joints 1 and 3. Sinusoidal signal gain $(-\pi/2)$ joint 1, and gain $(1-\pi/4)$ joint 3, see model in Fig.10-6.

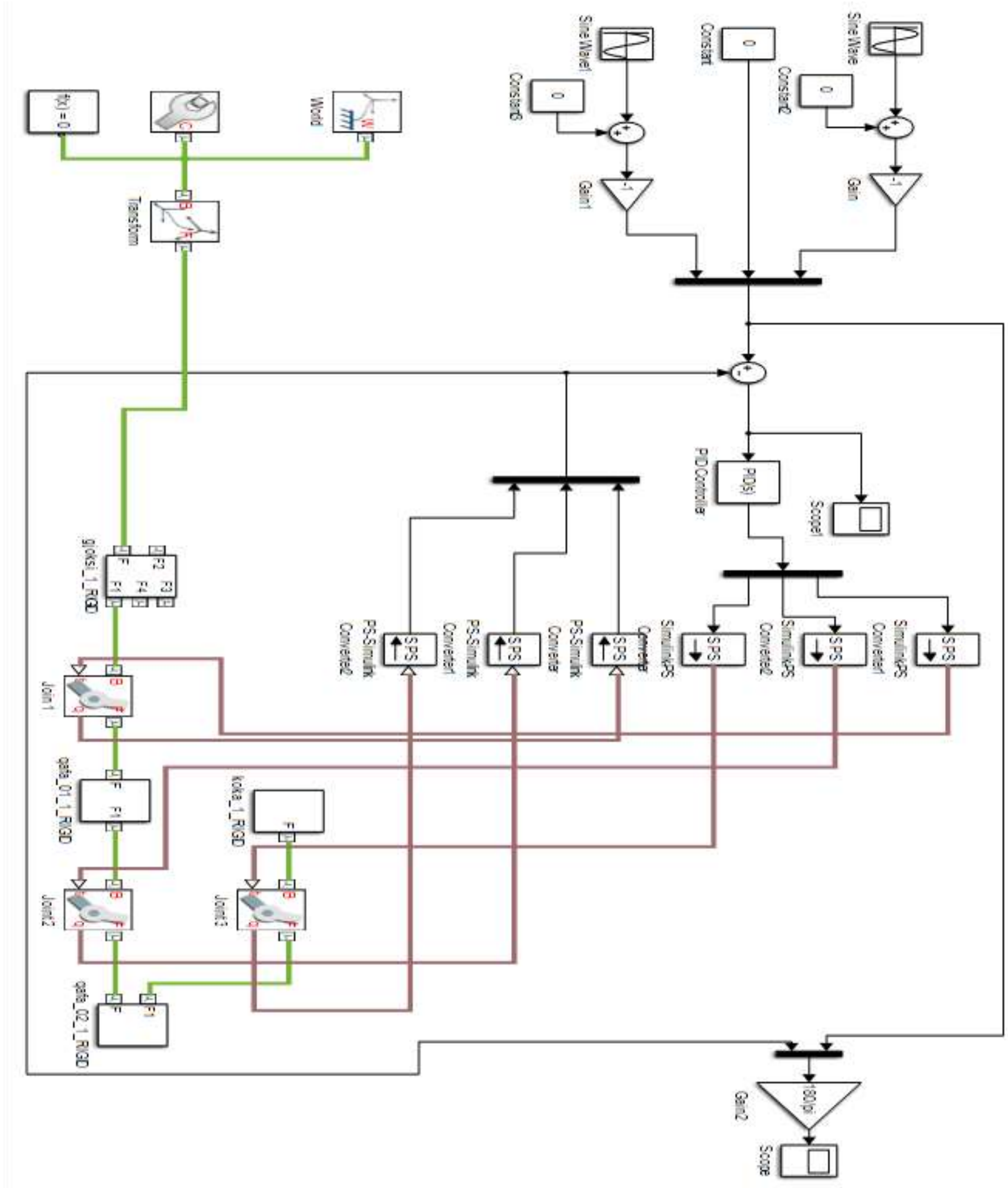
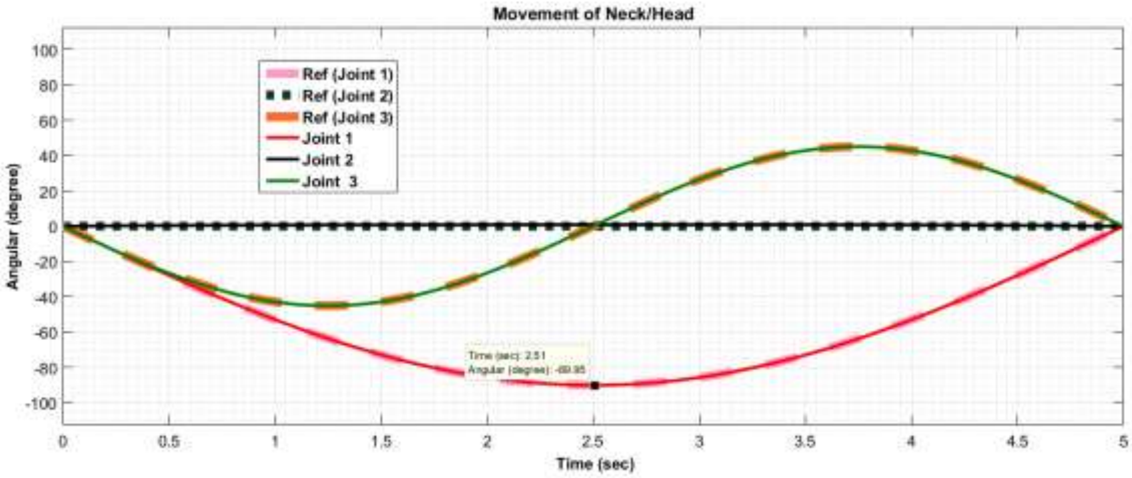


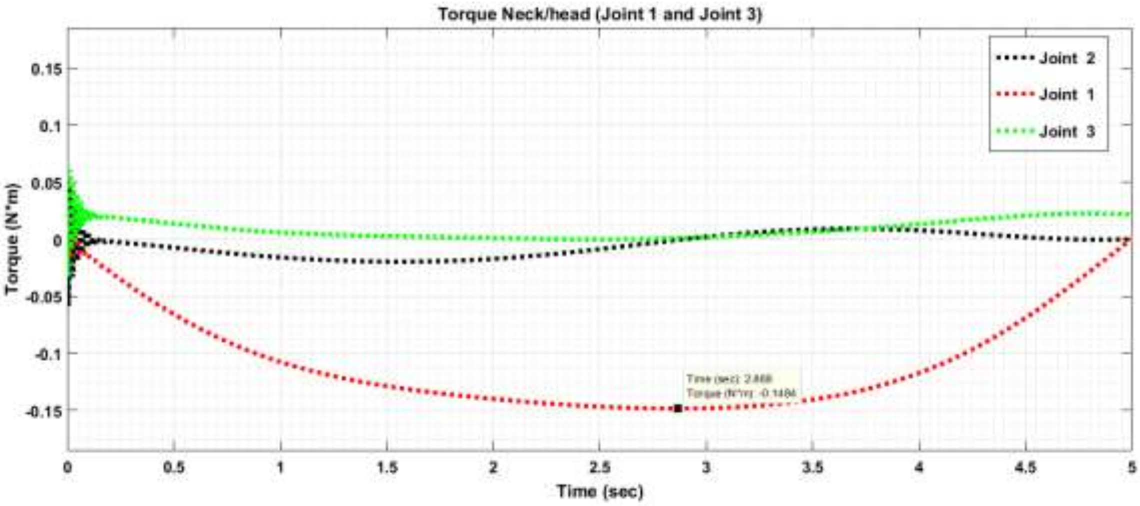
Figure 10-6. View of all blocks the model

The model contains the sinusoidal signal at joint **3** where there is a move$\theta_3 = 45^0$**,** whereas at joint 1 there is a move$\theta_1 = 90^0$.
Period of rotating moment of joint 3 is twice longer, while the amplitude is as half of the amplitude of the moment acting on joint 1 (Fig 10.7). Movement of the head does not have large vibrations, nor does it have waves with large amplitude in any of the tests reviewed.

Torque of the head in joint 1 reaches the maximum 0.15 Nm (Fig. 10-7, *b*), whereas the curve of angular shift is very smooth and shows the best movement performance (Fig. 10-7, *a*). This does not show so high values of torques, as the mass of the head is very light. The errors are very small (Fig.10-8).



a)



b)

Figure 10-7. *a)*The movement of Head/Neck and *b)* torque

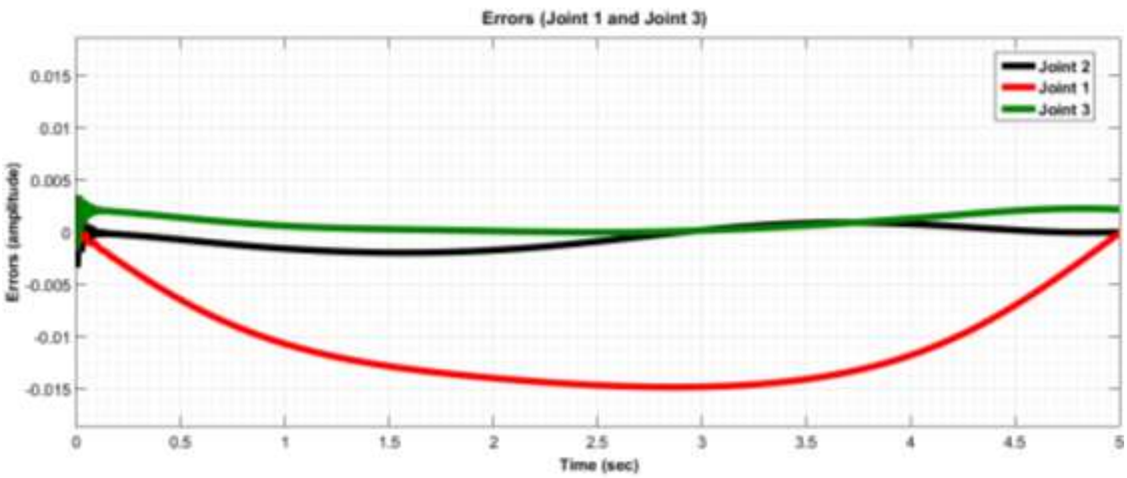


Figure 10-8. The errors of Head/Neck V2

10.4.1 Conclusion on test 2

Tests 1 and 2 indicate that the design of the head can move in different angles, with combination of two joints. With the participation of three joints, performing various movements of head, with similarity to the movement of the human head, creating opportunities for cameras to look in different angles. As in test 1 and in test 2 of the head/neck, no vibrations have been detected, performing movement of high stability.

This stability comes because of links that form the robot serial neck, they are short, and also because of the overall light mass of head/neck. It should be emphasized that stability is high, even when the head movements are carried out rapidly, thus approaching the speed of the movement of human head.

10.5 Summary

This chapter shows the tested movement of neck/head with Simulink, a tool of Matlab 2014b. Models are created for some special cases using the PID controller. Through the simulation of graphics transitional processes are shown during movement, and characteristics of performances during movement of the head/neck of the robot are presented. Analyses of the mechanical structure of the design of angular movements give different value of stability of robot head movement.

The movement of the neck/head in almost different speed and angles does not affect anything in stabilization of the robot.

11 Simulation of design (V3)

”All that is real is reasonable, and all that is reasonable is real”

Georg Wilhelm Friedrich Hegel

11.1 Introduction

This chapter shows properties of actuators of the arms of prototype three, marked shortly as V3. The maximum torque required for actuators has been calculated for setting in motion the limbs of the robot. The minimum value of torque required during head movement is also found. In addition, simulations of neck/head and arm have been presented in order to show performance of the movement. In the end, the range of joint movement and other features of the design have been given.

11.2 Selection of motors (V3)

The conclusion is that actuators RX-64 for arms and RX-28 for Neck/Head are suitable for this robot, taking also into consideration the low cost.

Figure 11-1. Arm V3

Arm contains four revolute joints and they are marked in the order presented in the Fig 6-6. Selection of the actuators is found by calculating the values of torques for positions requiring maximal values, to put in motion mechanical structure of robot arm.

Plots below show calculations of torques (1.269 Nm) for angular movement of 90 degrees, to raise the arm on the side, with different speeds, for time t=5s and 0.5 sec.

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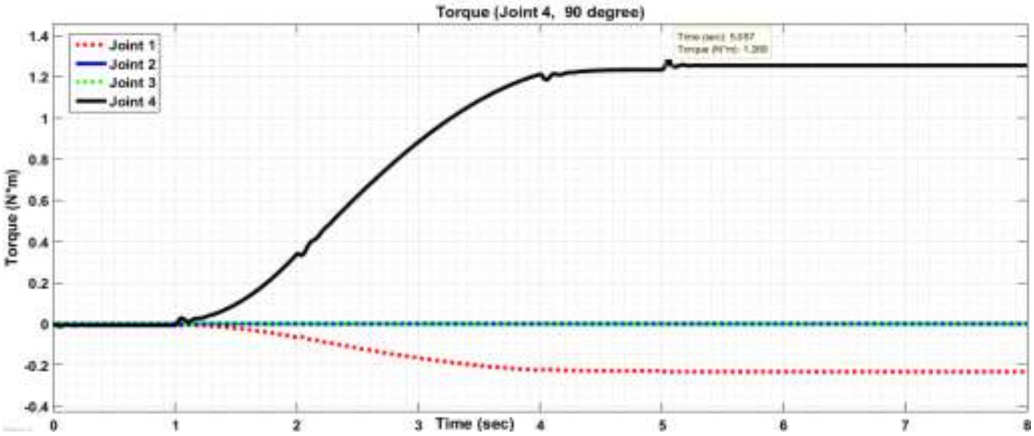

Figure 11-2. Torque in joint 4, in speed of 5 seconds

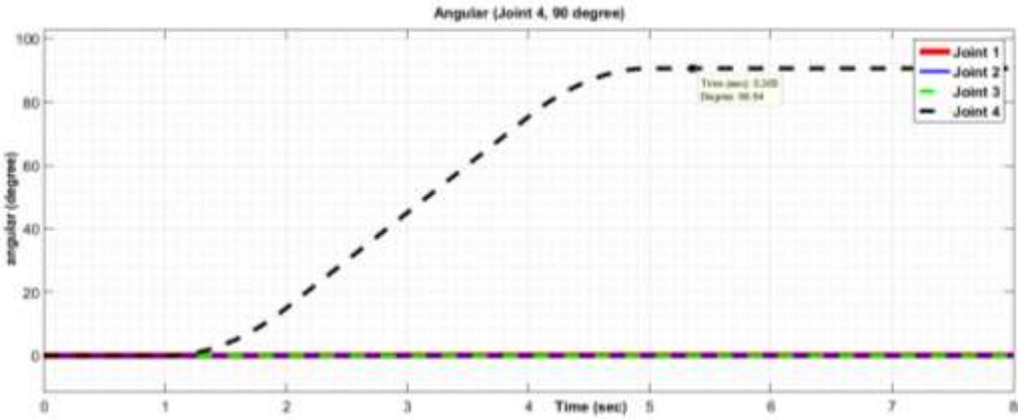

Figure 11-3. Angular movement in Joint 4

11.3 Torque and speed of arm

With increase of the movement speed, when raising the arm to the same angle with the same mass, values of torque need to be high. In transitory time from 1.269 Nm for the time of 5 sec, there is 1.956 for the time 0.5sec. The difference of torques for mentioned speeds is (1.956-1.269=0.687 Nm). Plots are given in the following figures (Fig 11-4 and Fig 11-5).

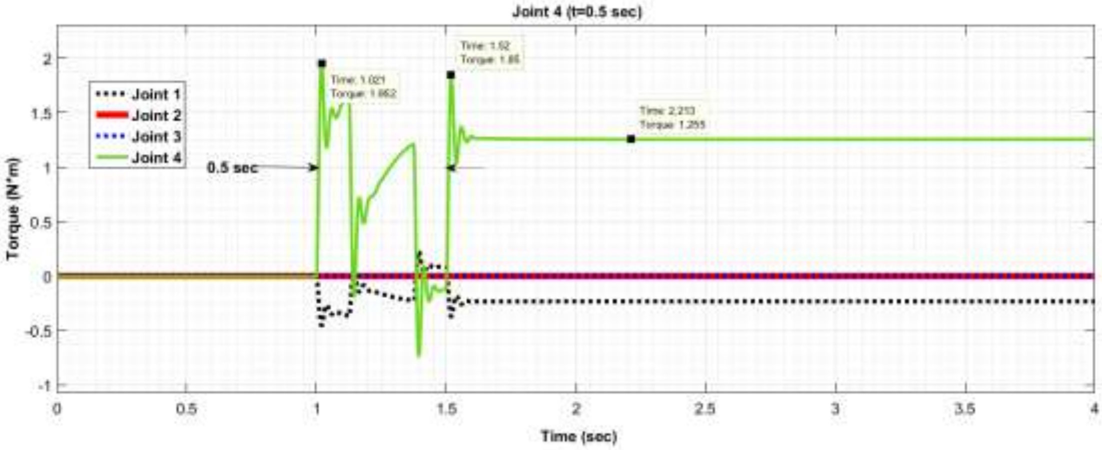

Figure 11-4. Torque in joint 4, in speed of 0.5 seconds

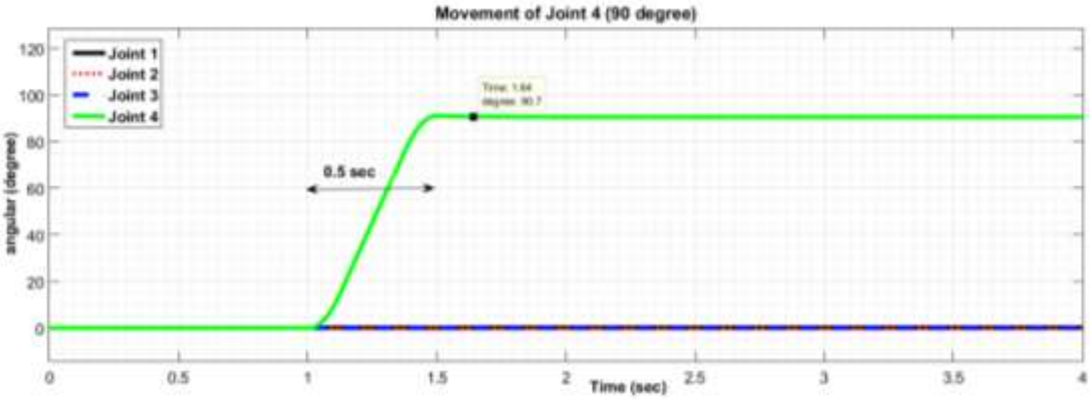

Figure 11-5. The movement of 0.5 seconds

From the calculations made, values of which are presented through plots, it can be noted that Dynamixel Rx-64 actuators have sufficient torque and are appropriate for the arms of the robot. The largest mass will be borne by motor 4 (joint 4). This motor during the raise of the arm on the angle of 90 degrees on the side, with torque of T= 1.269 Nm, is the maximum value of torque the motor should have (same value of torque have joint 3). This is the extreme case to calculate what should be the torque of the motor. Calculations have been made by doubling the real mass of robot arm where torque in extreme cases can reach a torque of 3.7 Nm.

11.4 Minimum torque on arm (V3)

Minimum torque value is 0.233 Nm at the motor on the arm, whereas the value of 0.1 Nm is minimal for the motor that moves the structure of neck/head. This value requires to have a motor on robot arm, in the position of elbow so that it raises the mass of forearm of 320 *g*, moving it over 90 degrees (Fig 11-6 and Fig 11-7).

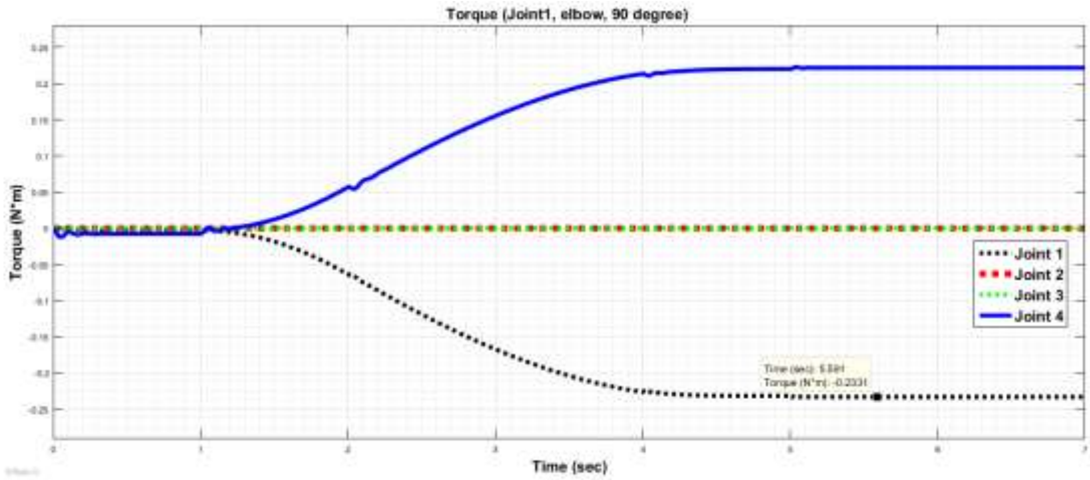

Figure 11-6. Torque in Joint 1

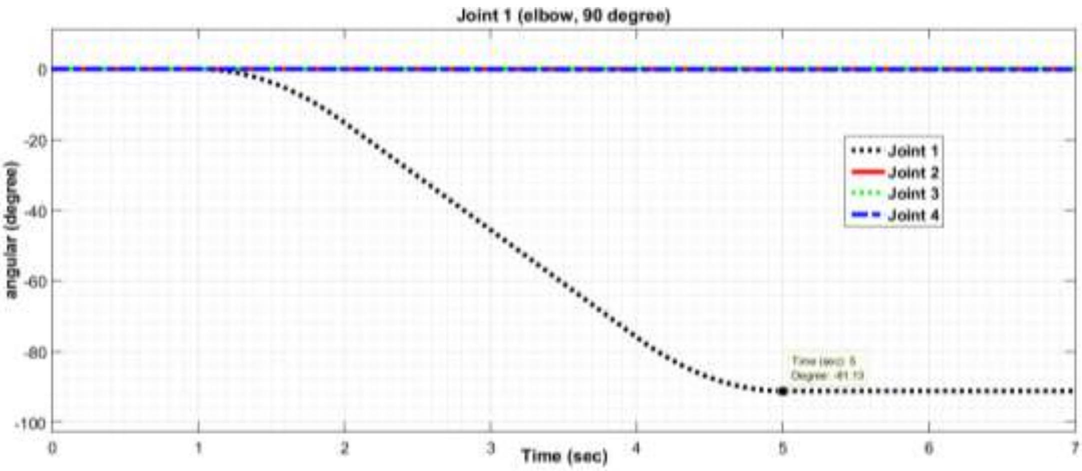

Figure 11-7. Angular movement of Joint 1

11.5 Neck/Head of V3

Neck/head has two joints, links are of small mass (Fig.7-4), short in length, and actuators can be selected with a lower torque. From calculations it is concluded as to what values can be proposed for the actuators. During movement of cameras in rectangular trajectory (joint 1 for 90 degree and joint 2 for 30 degree), the following calculations of torque will be given with approximately T=0.1 Nm. Values of torque have been provided on the chart, necessary for the movement of the neck during movement in square trajectory of cameras. They have been presented in the following graphs (Fig 11-8, movement) and (Fig 11-9, torque). Thus, torque for movement of the head is of small values, as links building the neck have short length and low weight. With the comparison of input-output values the error is obtained.

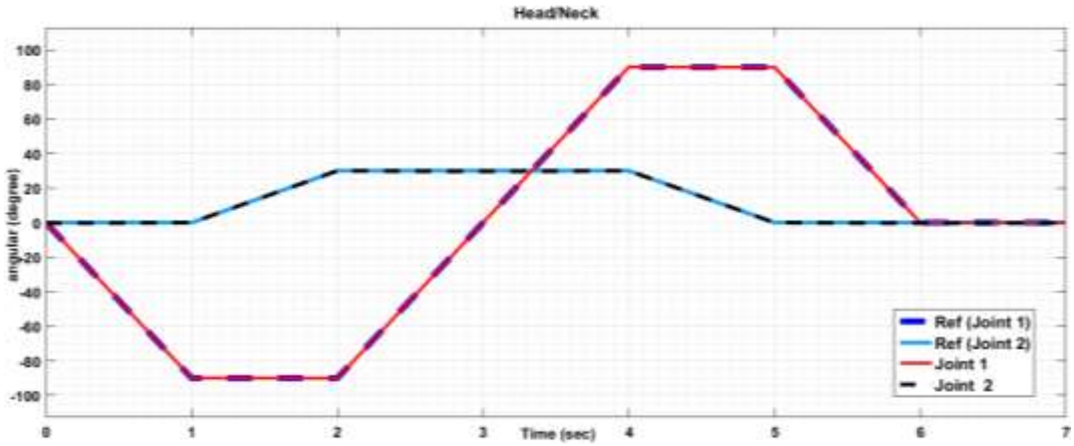

Figure 11-8. Movement in rectangular trajectory

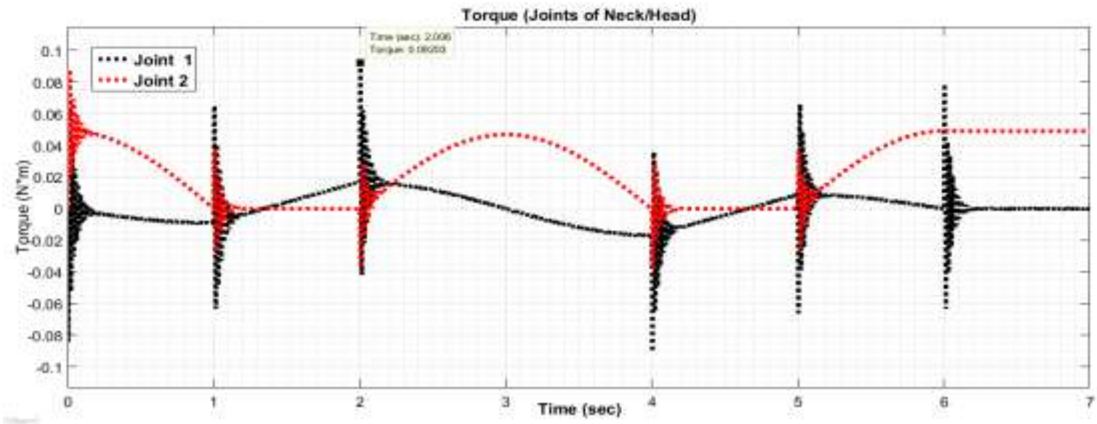

Figure 11-9 Torque in Joint 1 and 2

Error represents the performance of movement, in this case for movement in rectangular trajectory of head V3. The error is very small, of the order of 10^{-3} (Fig 11-10).

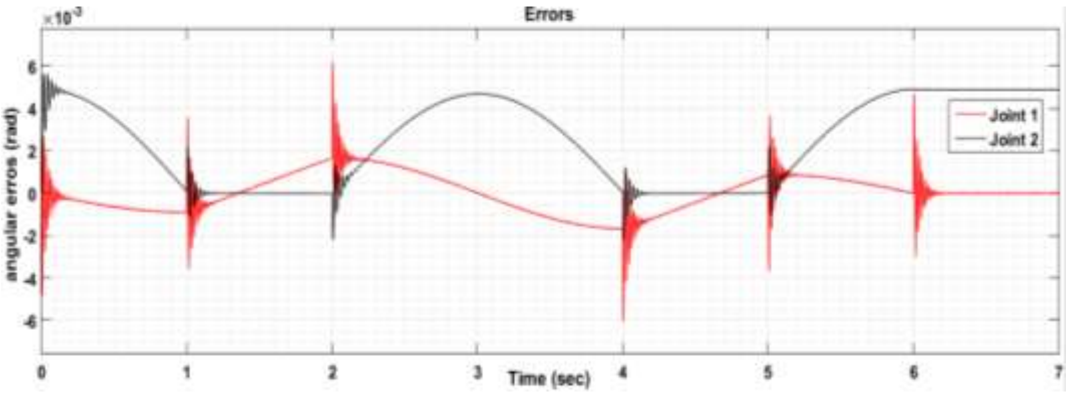

Figure 11-10. Errors in Joint 1 and Joint 2

11.6 Summary

Torque values have been calculated in the simulations of the third prototype (V3), and they are very low due to the low weight of the links building the mechanical structure of shoulder and head. The calculated torque values show that Dynamixel motors have sufficient torque in order to put the arm into motion in high speed. The head has a very light weight compared to the second prototype, thus the loads for the neck motors will be very small. This chapter also includes shorter explanations in order to evade repetition of explanations provided in chapters 10 and 9.

12 Summary and Outlook

"To read means to borrow, to create out of one's reading is paying off one's debts"

Georg Christoph Lichtenberg

12.1 Introduction

This chapter provides comparison between the three designed versions; V1, V2 and V3, including their advantages and disadvantages. Interface of the third prototype, mass distribution, features of actuators have been explained. Prototype three is currently under construction.

Neck/head have been described for some humanoid robots, built by research institutes worldwide. Each of these robots has distinct designs, having different dimensions and materials they are constructed of, and different mechanical features.

The neck/head is the most important part for movement of cameras, and to give the humanoid robot a human view. Therefore, different types of neck/head have been constructed striving to reach the best possible results.

The main characteristics for these various types of neck/head have been collected for these humanoid robots, such as;

DOF-degree of freedom,
Mass,
Materials
Dimensions
Motors
Interface.
Cameras types

An overview has been provided for Neck /head of other robots and of Archie.

12.2 Construction of humanoid neck

Enhancement of humanoid robot is an attempt to copy as much as possible features from human being, such as; motion, intelligence, and the appearance too.

Complexity of motion the human body makes, is closely connected to the complexity of construction of its body. Nature of construction, mass distribution, joints, muscles, receptors allow for human to perform more complicated moves, still unreachable for robots. Lots of studies have been made related to analysis of human body in many aspects in order to obtain a more simplified model with the aim of applying it to Humanoid Robots.

One of very important parts of Humanoid Robot body, where parts of the body take the human view, is the head and the neck. Head and neck are important not only because they give the robot the human appearance, but because the "eyes" are always mounted on the head.

Construction of the head and neck includes;

a) Mounting of the head and neck that is determined by the view of the robot. This means that depending on how the robot looks, in the same level it will be accepted by people in the environment where it operates.
b) With defining of the degree of freedom - DOF of the neck, the neck is given the opportunity to move the head (and cameras) of the robot. Most Biped Humanoid robots, in addition to degree of freedom in the neck, have special systems for moving the eyes.

While designing the head, one of the biggest difficulties is definition of the power and the speed of motors, acceleration of various joints. In such parameters, the best case would be approximation to natural values the human being has on the neck and on the head, the manner of rotation of the head.

The design should be in that way to have enough space for placing or 'packaging' the electrical components, namely, to make the best use of space.

While the next stage of Archie, the reconstruction of a new prototype Archie, would include a new construction to be much closer to all characteristics (movement, mass distribution, skeleton) of a human body.

Material of robot's skeleton must be lighter compared to the current material. For example biped Lola robot has a part of legs made of plastic of quite light weight. The new prototype of Archie in the future must include rotating joints and linear actuators and pneumatics to enable precise movement similar to human muscles. At majority of robots, the batteries are installed on the back of the robot, such as ASIMO, Lola, HRP-4 etc. Mechanical design of robot’s head includes determining the degree of freedom.

As Archie was designed according to real human dimensions, in particular referring to the upper body and low body limbs, it enables a harmony of mass and length distribution of the robot. Hence, a COM (centre of the mass) is reached as regards to height from the floor similar to humans. V3 has e serial neck, it consists of two actuators and two links. One of the neck motors is part of shoulders and is located at the shoulder level. In this view, it has been managed to have two links of the neck longer, so that the workspace is sufficiently large. At the three prototypes, one of the joints is inserted at the shoulders, but it should be counted because it provides the neck with 1 DOF.

When neck/head mass is taken into account, the motor was counted too. In fact, if this motor is not foreseen, then the mass of the neck/head will be even smaller, at least for a value of 150 g. Parallel neck of V1 is usually used for movement of heavier loads.

These necks are also distinguished for accuracy in movement, but having a smaller workspace. Thus the design of V1 has been given only as an option for future research.

The earlier proposal for this design has been excluded to use belt transmission on the shoulders. The reason for such exclusion is that they occupy a large space, the design becomes more complicated, and during the work more shakes are caused. The design is simple and practical for use (assembling and disassembling, for repairs and change of electrical parts) and study after its construction.

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12.3 Anatomy of the Human Neck

Human neck has a complex structure composed of seven rings piled one above the other forming a pile, serving to connect the head to the body. Muscles playing the role of the motor to move the head are integrated on the neck. The muscles also keep the head up and turn it to different directions to orientate the senses of hearing, eyes and to gather information as per human needs. Muscles are tissue segments of varying length and conduct make different movements, of course specific for each muscle. Complexity of the neck is further increased with the nerves and blood vessels. They can be compared in robotics to the information system, and to the electrical system, all of them connected to Main Controller.

Muscles depending on the shape and size, and the position they occupy on the neck, take the denominations in the science of anatomy.

They have been studied extensively in the models in order to apply them practically in humanoid robot.

Movements made by the neck, with the help of muscles and rings connected with intervertebral material are as follows; flexion, rotation, lateral flexion, circumduction, extension with participation of muscles indicated on the Tab.12-1. Neck is built of such a structure as to absorb the gravitational impacts; its base is on the disc marked as C7 sitting on the rings of the body trunk. In table (Tab.12-1) some data is given for human neck.

The skeleton of human neck consists of seven vertebra discs piled over each other, named as C1 - C7, where C1 is called Atlas being connected with the head and has 1 DoF, while the six other vertebra discs have 3 DoF. Vertebra discs are connected with each other through ligaments and muscles.

Each vertebra discs from C2 – C7 has 3 DoF, as they are piled over each other, in the middle contain a fluid called synovial fluid making the human neck highly mobile, elastic and absorbent of physical pressures. Range of motion is given in table (Tab 12-2).t444

Each of the discs have narrow angle of movement, but on the top of this pile (cervical lordosis) the discs create a wide angle of movement of C1 (they can be considered as the end of effector), as the basement where head is connected (Tadesse, 2013.). Atlas (C1) is connected to head bones and majority of moves occur at this ring.

Table 12-1. Muscles helping the motion (Flores & Fels, 2014)

Joint Motion	Prime Movers	Axxf
Flexion	Sternocleidomastoid Scalenes Longus colli Hyoid muscles, etc.	Scalenes Hyoid muscles
Extension	upper Transversospinalis group Splenius capitis Levator scapulae , etc.	Transversospinalis group Levator Scapulae
Rotation	Trapezius, Sternocleidomastoid Scalenes Trapezius, etc.	Scalenes Transversospinalis group
Flexion	Levator scapulae Rectus capitis lateralis	Transversospinalis group Rectus capitis lateralis

12.4 Artificial muscles

Human neck has over 20 muscles and 10 bones. The head contains a much more complex design taking into consideration the mouth, facial expressions and eye movements. Study of neck movement has been directed by many biomechanics towards the dynamics and kinematics of the neck. The knowledge gained can be practiced into curing the patients in case of injuries in traffic and during sportsmen training sessions. Majority of models of human neck are approximated with the neck of robots with 4 DoF, every second vertebra of human neck gives 1 DoF (Tadesse, et al., 2010). Majority of latest robots have 4 or more DoF on the neck, while the other types of robots have 2 and 3 DoF.

Table 12-2 Range of motion (Flores & Fels, 2014)

	Tilt	Roll	Pan
Range of motion	-71^0 to $+103^0$	$-/+63.5^0$	$-/+100^0$
Max. velocity	$352^0/s$	$352^0/s$	$352^0/s$
Max. acceleration	$3{,}300^0/s^2$	$3{,}300^0/s^2$	$3{,}300^0/s^2$

There are Humanoid Robots with motor on the neck and in the eyes, where the tilt and pan movement is mainly carried out on the neck. Neck should create quick pan motion and slower tilt motion. The speed must be higher in the eyes, because the eyes move faster than the head in direction of sight. Movements of the head are performed when the neck moves along the axis system coordinates OX, OY, and OZ. They are usually called; roll, pitch and yaw movements; these denominations are used in the description of movements of airplanes and ships.

12.5 Head/Neck at some Humanoid Robots

Biped Humanoid Robot is the first step for building the robot resembling to man. This stage includes installation of all necessary sensors for direction, orientation and balancing of the robot. Other stages are more important for humanoid robot to have not only the shape but the view too, such as the human face, as an important factor to be associative. System of audio-visual sensors includes hearing, speaking and view of the robot. Neck and head construction gives the human shape to the robot and they have particular importance for the robot. Face also represents quite a complex construction. Complexity of face construction is directly interrelated with selection of materials it is built of, such as; skin, lips, eyebrows, teeth, ears. It is related as to how they will be put into motion: jaws, lips, eyebrows and face emotional expressions performed through movement of face muscles. All movements occurring on the face must be carried out through motors, micro-motors or artificial muscles. Artificial muscles (Tadesse, Y, 2009) and their construction is related to study of lots of materials behaving in a similar way to natural muscles of the human face.

Nowadays, it has become a rule that the whole body of robot is built in a module, and this becomes obvious in many humanoid robots. The best example is NASA's Valkyrie Robot (Ackerman, 2014), it's assembling and disassembling is easily performed, and in cases of defects are easily localized (Lohmeier, Buschmann, Ulbrich, & Pfeiffer, 2008). Head/neck contains electric part including cables, motors and sensors.

The design of the neck and head is simpler as it includes only providing the possibility for execution of movements; roll (along OX axis of coordinate system) and yaw (OZ). On the body of Robot in the future prototype, it will be necessary to install the sensors to enable orientation and approximation to human senses. A Biped Humanoid Robot Lola has 50 sensors integrated into all its body, being a successor of Johnnie robot. They have the same number of sensors, but some are replaced by more advanced practical sensors, and the electronics has further developed in interfaces of sensors. Increase of the number of necessary sensors expands the possibilities of the robot to be more skilled in the environment where it operates (Lohmeier, 2010).

12.6 Serial, Parallel and Hybrid Neck

Necks of Humanoid Robots based on the manner of their construction, position of actuators, can be grouped into serial, parallel and hybrid.

Serial neck actuators stay one after another in series. Parallel neck actuators stay parallel to each other, fixed on a base and on the other side fixed on the platform where the head is installed (Fig. 12-1). Hybrid neck is a combination of parallel and serial actuators. Neck spring (parallel neck) where the spring begins from the base and ends at the platform where the head is mounted is similar to the parallel neck.

Serial neck occupies less space, while parallel neck is built according to the design of the flight simulation equipment for driving the vehicle, for preparation of pilots and vehicle drivers and is called 'Stewart Platform' (Martinez, et al., 2012). Stewart

Platform consists of linear actuator fixed in parallel between two platforms where one of them is immobile.

The platform in the base connects with the body of robot, while the head of Humanoid is placed on the other side. Of course, each robot has its own particulars depending on the need and purpose of designers of the robot. Some designers require head designs to be as close to human nature as possible, the others pay more attention to eyes in order to achieve a perfect visual perception. Parallel neck makes soft moves, very similar to human neck where pneumatic actuator can be used. The most common type of parallel neck contains 6 DoF, with rotary and linear movement through three axes (Lee, et al., 2001).

In addition to rotary axis, the parallel neck also has axis for linear movement. Through the joints, movements are performed for head orientation such as; pitch, yaw, roll, and elevation.

For example humanoid robot Muecas, and one of the constructions proposed for robot iCub etc. have parallel necks. Fig 12-1, shows the neck of iCub robot, where all motors are seen to be fixed at the base, and the base and platform are joined with a couple of spherical joints connected to an axis. The platform is connected with the head of the robot and is orientated by 3 axis fixed down to base. The construction of the neck was made for robots of small dimensions. The neck has 7 cm up to 9 cm and has 3 DoF giving quite a small workspace. The parallel neck has a high preciseness, is highly compact, with high stability during the movement. The inertia of parallel neck is small during the speedy movements. (Beira, et al., May 2006)

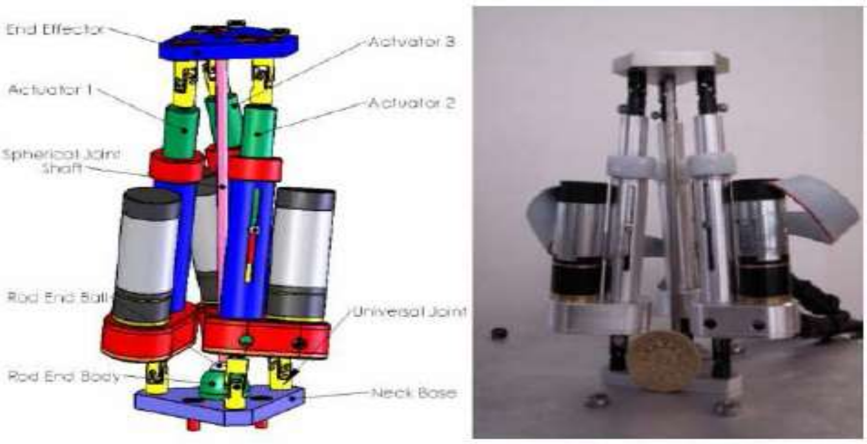


Figure 12-1. The example of parallel neck of iCub

The neck of James robot is quite elastic because of the steel spring being an imitation to the vertebral discs of the neck. The spring is connected with steel tendon imitating the human neck muscles. The following Fig 12-2 presents spring neck (Nori et al,. 2008)**.**

The head of James has a mass of 2kg, equipped with two eyes-cameras with possibility of pan and tilt movement. The neck has 3 DOF which can perform rotary movement around OZ axis. James robot is an attempt to imitate as much as possible the human neck, head, and hand, so it is a biologically inspired robot. Its construction material is aluminium (Nori, et al,. 2008).

This robot has in total 23 motors (22 DoF) with torque broadcasting in joints by toothed belt and steel tendons. It is also equipped with two digital CCD cameras (PointGrey Dragonfly), remote head, and with proprioceptive, kinaesthetic and tactile inputs.

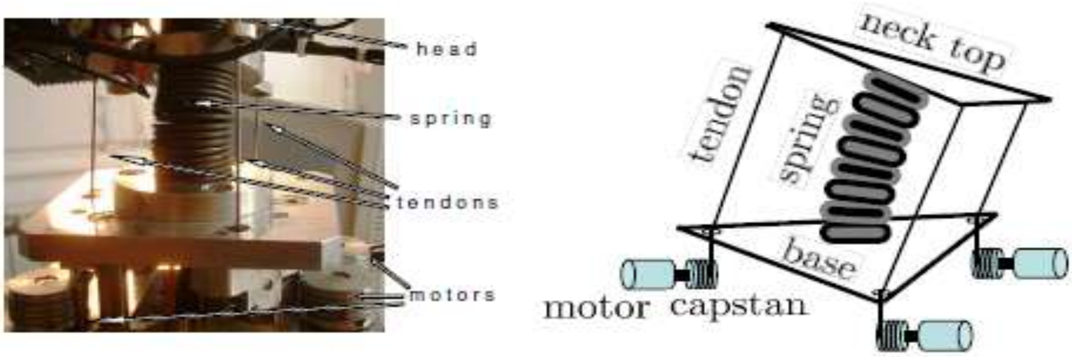


Figure 12-2 Image of spring neck

Spring neck is often categorised as parallel neck. The efforts to imitate the human head by the engineers are limited: by the type of material it is built of, which must be as light as possible.

The weight of the head impacts quite much the general stability of humanoid robot, especially while in motion. Neck/head and also the whole body of the robot must have the mass distribution as symmetrical as possible.

This fact must be taken into account while assembling electronic parts; controllers, cameras, audio-visual and other sensors on the head.

As the parallel and serial necks have their drawbacks, efforts have been put into designing a kinematic architecture combined with serial-parallel which are known as hybrid necks. Hybrid necks aim at making moves which are as close as possible to human movement.

The parallel designs have a limited range of movement in spite of their dimensions. The actuators are ranged in orthogonal way where the stacked design requires high torque motors on the base because they are loaded by the weight of motors. The links are nearer to the head. Intending to have a wide range of movement, a serial neck has been chosen in V2 and V3 for Archie.

Humanoid robots Mertz, Twente have hybrid designs on the neck. Head’s Twente has 7 DOF in total while 4 DOF are on the neck containing a differential drive. This robot makes all movements of the head, such as; pan, lower tilt, the roll, and upper tilt (Reilink, et al., 2010).

Head of Mertz has in total 13 degrees of freedom (DOF), head/neck has 9 DOF and 2 of them are on the neck. The neck makes tilt and roll movements in support of series of elastic linear actuators forming a differential joint. Face of Mertz promotes social interaction. Mertz has two digital colour cameras (Point Grey Dragon-y) with FireWire interfaces and a resolution 640 x 480. The eyes move in pan independently, while the tilts move depending on each other (Aryananda, February 2007). Building of head/neck of Mertz has large differences from the construction of the human neck and head, as such cannot be used in Androids (Flores & Fels, 2014)

The Humanoid Uma has a hybrid neck of 3 DOF, designers were inspired from industrial robots. Uma has high stiffness and good dynamics, a design minimizes 'wobbling' problem which are seen at actroid robots (Flores & Fels, 2014).

12.7 DOF of Head

A considerable number of simple robots have simple head constructions and are mainly in the function of cameras. The constructions are simple at biped robots, while anthropomorphic robots are much more complex in the part of the head, especially in design of the face.

Albert HUBO is an advancement of HUBO robot only in the part of the head having 31 DOF, 3 DOF are located on the neck (Oh , et al., 2006)

The number of motors is placed depending on the purposes of designers to ensure the neck and head movements as similar as possible to the movements of human beings.

The neck moves cameras based on the view of the scene in the best way possible. In most robots there are stereo cameras of high resolution. Some robots are equipped with two cameras for each eye for the wide and narrow angle of capturing being regulated simultaneously. Below are given some features of the head part at different robots; at Johnnie and HRP robots tilt and pan moves require the stereo cameras with 2 DoF.

HUBO has 6-DOF on the head, having 2 DoF on the neck, in the same way iCub has 6 DoF on the head, but 3 DoF are on the neck

ARMAR-III has 7 DoF on the head, out of them 4 DoF are placed on the neck.

The robot CB has 7 DoF, out of them 3 are on the neck, so the cameras move with 2 DoF each, with possibility that each camera makes pan and tilt movement. However many research institutes have built only the head of Humanoid Robot. It is aimed at development of the head to the highest degree of imitation of human being, including the face. Robots have only the head region built; the number of DoF often exceeds the total number of DOF-s in the entire body. This fact indicates that construction of the head/neck part is not only complicated, but also quite important for Humanoid Robot in order to be as associative as possible to the man. In this sense, the robot is as close and acceptable to man as possible.

The Cog robot has in total 22 DOF (two 6-DOF arms, a 3-DOF torso), the head has: 4-DOF on the neck to conduct its roll, yaw, pitch movement, and 3-DOF for eye movement.

At KHR-3 HUBO robot, at the part of the neck has two joints for realization of the pan movement (planetary gear, with reduction of type 104:1) and tilt (Harmonic Drive 100:1 input gear ratio Pulley-belt 2:1) with the motor having power of 10 W.

KHR-3 in its eyes has pan and tilt joints (Planetary gear 256:1), while it has an input gear ratio for tilt movement 1.5.1 (Pulley-Belt). The battery and PC are installed on the chest part, different from Asimo that has the battery on its back.

The neck of ASIMO (according to the data from 2001, the neck had 2 DOF) has 3 DOF, according to technical information (Division), September 2007), (P, Ill-Woo. et al., 2005. The most costly and important part playing the role of orientation of the robot is "the eye" of the robot and that is why special attention is paid to visual system. There are different head designs, but something that makes these designs similar are the couples of cameras. Most of the systems which use cameras at humanoid robots with narrow and wide angle of view aim at studying the vision, as an effort for approximation of foveal and peripheral human vision.

The robot Kismet has the foveal vision in its cameras installed in the eye, while the peripheral vision part is fixed on the head, its movement is realized through neck movement.

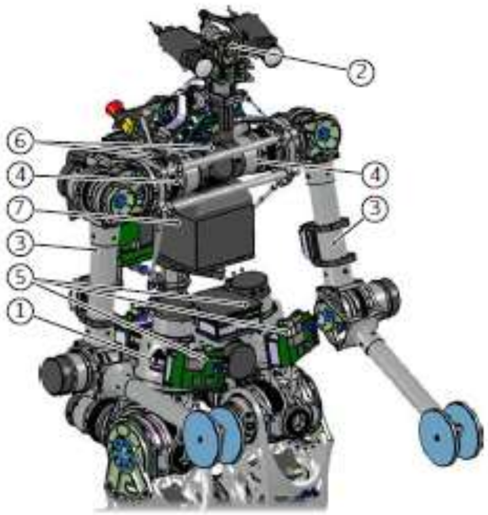


Figure 12-3. LOLA biped robot (The institute of applied Mechanics, 2010)

Some Humanoid Robots usually have the visual system built quite simply with cameras and have only one stereo camera. A part of these robots are biped after having achieved the dynamic stability of the robot, they swiftly built the visual system of robots to meet the perception. This group of robots includes the following: HRP-2, Johnnie, Justine, Lola. There are robots which instead of eyes simply have an occasional display with robot.

As the official web page of Technical University of Munich in Germany states, they have built the humanoid robot LOLA based on results of JOHNNIE-project. Lola can overcome the obstacles in height of 4 cm, while its body height is 180 cm resembling the adult man dimensions.

Humanoid robot LOLA (The institute of applied Mechanics, 2010) in total has 25 DOF; in its legs it has 14 DOF (degrees of freedom), on shoulders 4 DOF, pelvis has 2 DOF and 3 DoF are on the head for movement of stereo camera, for pan and tilt. Movement speed is 3.34 km/h, while the weight is about 55 kg. Humanoid robot Lola can avoid obstacles by jumping over them. In its maximum speed it reaches to have a step of 65 cm (Fig 12-3). It maintains its balance with one foot standing on the ground while the other steps on a height of 4 cm. The robot can preserve the balance when a low force is applied over it by pushing to the opposite direction. With a degree of freedom in the area of toes is not only that the robot resembles the human feet, but it also reaches a higher stability while it is walking. Camera of humanoid robot is Kinect Camera ASUS Xtion. It is understood that each resemblance to human architectural kinematics is also approximation to human dynamics and stability.

A discussion will follow regarding the head of Humanoid robot ROMAN (Mianowski, et al.,, 2007), and about some features of construction of ROMAN robot. ROMAN robot has on its neck 4 DoF, the diameter of eyeball is 46 mm (human eye has the diameter as half of this). Within 'eyes' are the cameras installed in weight of 12 g, the iris of camera is 16 mm. The total weight of one eye and motor is 150 g, pan movement of the eye is 40 while in tilt it is 30 (Mianowski, et al., 2007).

Speed of robot eye movement is closely to obtain the view from the environment, so that as many defects as possible are overcome such as blur, vengeance movements. Hence, it is understood that all features of robot cameras need to be taken into consideration, the part of camera calibration and obtaining of photograph as qualitative as possible. The robot takes image directly connected to quality of the view from the camera. The eyes move in direction of the scene or the object speedily, thus they immediately focus the wanted viewing target. Peripheral cameras are often movable and the foveated cameras are immobile such as the head of the robot Kismet. Cog robot has both of them movable, the foveal and the peripheral.

The data for ASIMO robot is quite limited; such information is the secret of Honda Company. The company has advanced its humanoid biped robot during about 3 decades up to Humanoid anthropomorphic. In 2012 it marked the 10^{th} anniversary of enhancement of ASIMO robot (ASIMO 10th Anniversary Video, 2012).

Development of Honda company robot has changed quite much from version (e.g. Honda Humanoid Robot, EO, E1, E4, P1, P2, P3, ASIMO version 1.2 and all-new ASIMO etc.). Another issue in Humanoid Robot Asimo is that it has changed in the weight, in height and has improved the performance by demonstrating the way of going upstairs as it may be seen on the photo of the website of Honda company (HONDA, 2015). Reduction of weight has been followed directly by changing the material used for construction of the robot into a lighter weight material.

To obtain the view with in depth information, Asimo was equipped by two HD cameras (720 x 1080) on the head and a range-finder (HONDA, 2007). For the robot to have orientation in space, it got equipped with sensors such as; accelerometer, gyroscope and inertial unit (ASIMO, 2013).

Three sensors are located in the lower part of the body of robot, close to the centre of mass. It is equipped with 6 ultrasonic sensors, 5 are on the back part and one on the front part (Hirose, et al., 2006). A laser to detect obstacles walking on the ground, is located in front, they are distance sensors to detect the obstacles. ASIMO also has 4 other sensors of force placed in arms and legs, and one infrared sensor for detection of obstacles (Le, 2013). In 2011 the last version of robot called All-New ASIMO, was managed by Honda Company to improve the acceleration while running in up to nearly 9km/h increasing from the previous version for 3km/h. (Honda, 2012)

Hands of the robot contain tactile and force sensors in the palm of the hands and in each finger. Fingers move independently, performing movements of hands and the body with high ability, such as; taking the bottle with a hand and removing the lid. Many sensors integrated in the body of the robot are: visual and audio, tactile sensors. They have enabled to recognize faces and voices of people. The ability to avoid the collision by predicting the trajectory of walking for few seconds of a person that is interrupting its way, has increased even more the skill of the robot. The avoiding starts quite a time before the crash and it is not necessary to stop walking. ASIMO of the version of October 2011 has 57 degrees of freedom (the previous version had 34 DoF), it has a weight of 48 kg (the previous version had 54 kg). This data about ASIMO is not complete; it is available in all websites that speak about Honda Company. This humanoid robot is a part of presentation of producing capacities of company.

QRIO (Robot of small dimensions) is a product of Sony Company; it contains 38 joints, with length of 58 cm, and weight of 6.5 kg. It was built to be associated with people. This robot has four joints on the neck. Its eyes are fixed; it means that the movement of the eyes is carried out through movement of the neck (Geppert, 2004). QRIO

The robot ARMAR III has the serial neck with 4 DoF; The neck is 3 DoF in the base part and 1 DoF in the upper part of the neck. The rest enable the neck to move along the axis, and the sway of the head (Fig. 12-4). The movements enable the robot to make movements as human as possible, looking down and looking up. The below picture provides the neck of the robot Armara III, (Albers, et al., 2007).

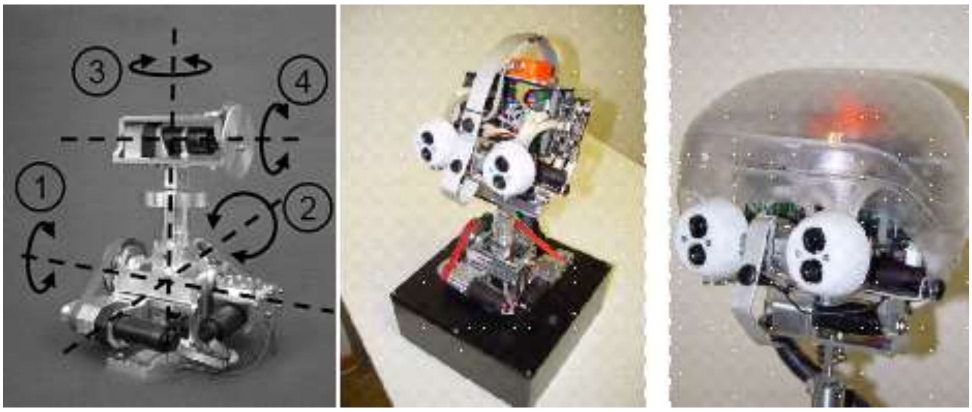


Figure 12-4. The neck of the robot ARMAR III (Albers, et al., 2007)

Four cameras are installed on the head for wide and narrow angle of the view, 2x2 cameras for eyes (Point Grey Research Dragonfly camera) (Asfour, et al., 2006). The cameras can transmit colour images with resolution 640×480 at 30 Hz.

Cog project since 1993 (MIT Artificial Intelligent laboratory in the USA) does not pay attention to stability and walking in two feet. But it is orientated to the part of upper body making efforts into applying the knowledge from cognitive and biologic science into robot in order to create a robot that will learn thinking (Kemp, et al., 2008).

Table 12-3. Data on full size bipedal robots

Robot's Name	*Height (cm)*	*Weights(kg)*	*(Neck) DOF*	*Arm (DoF)*	*Walking speed (m/s)*	*Operating system*	*Cost*
KHR-2	120	54	2	4X2	0,27	Windows XP	High
KHR-3	125	55	2	4x2	0.3472	Windows XP and RTX	High
HRP-1	160	120	2	7x2		Linux	High
HRP-2P	154.96	Head (1.2) Total 54.1	2	6 x2	0.1825	ART-Linux	High
D2008	57	3.5	2	´4x2	0.43	-	COHR
Reem-B	147	60	3	5x2	0.416667	ROS	COHR
CHARLI 2	141	12.1 (upperbody 5.34)	2	4x2	0.3889		high
Lola	180	55	3 (planned)	3x2	0.9167		High
ARMAR III	175 (upper body 70)	40 (upperbody) Head (1.6)	4	7x2	1	Linux, RTAI/LXRT-Linux, Windows, Mac OS	High
Design V1, V2 and V3							
Archie (V1)	126 (51 upper body)	20 (4.5upper body)	3	5x2	0.8m/s	Linux	COHRE
Archie (V2)	126	20.3 (4.8upper body)	3	5x2	-	-	-
Archie (V3)	126	18.5 (2.9 upper body) (0.261 head)	2	4x2	-	-	-

Humanoid robot called CB-i (Computational Brain Interface) in total has 51 DOF, 2×2 DOF eyes, 3 DOF neck / head, 1 DOF mouth, 3 DOF torso, and 2×6 DOF hands. CB robot also has four cameras in both eyes, thus, foveal and peripheral (Kawato, 2008). Aiming to build a robot that is social, Meka S1 has designed something in this aspect (the newest version is even more advanced known as S2). In Meka S2 version, there are 5 DoF (Robot Interaction, 2014) on the neck, integrated DSP controllers, zero-backlash Harmonic Drive gearheads. (Owano, 2011).

The head, neck of the robot S1, and the eyes, having in total 9 DoF which it manages to make the necessary movements. In the visual system it contains Firewire Camera of high resolution (1328x1048 at 23 FPS), integrated DSP controllers. To express as human as possible gestures through eyes-cameras, it has 3 DoF for quick movement saccades, smooth pursuit, 4 DoF on the neck and 2 DoF on eyelids.

The robot Meka S1 has the head of humanoid robot with the dimensions of a child (Meka, 2009).

Study of robots in the area of Head/Neck with the cameras installed on a plate and the eyes are not mobile, serving as a starting point for designing the robot, and in studying of features of the neck zone (Tab.12-3).

As a result, heads of humanoid robots which are much more complex than Archie have been studied on the part of the neck, where majority have 2 DOF.

The table above (Tab 12-3) provides some robots with similar characteristics to Archie, including; price, simplicity of design. The intention is to present robots similar to Archie. However, the other robots on the table have only been provided for purposes of comparison, considering that they are more advanced, such as KHR-3, KHR-2, Lola, etc.

Hence, based on comparison of values presented in the table, Archie robot, with a simple construction and a low cost reaches a good movement performance. A high performance is recorded in torque with low values, light loads in the motors. The speed of head movement can be high without causing negative effects in stability.

Mass of the links plays a particular role in robot's stability and in the dynamic performance while moving. Thus robots have different weights, length and different dimensions in general. They will be provided in Table 12.3, taken from; (Park, et al., 2005)**,** (Hirukawa, et al., 2004)**,** (Scholz, et al., 2009)**,** (Han, 2012)**,** (Tellez, et al., 2008)**,** (Lohmeier, et al., 2009)**,** (Kim, et al., 2005)**.**

12.8 Comparisons V1, V2 and V3

In the course of simulation calculations, often a greater mass is taken than the one the design really has. In this view, the intention was to take larger and more accurate values of the torques. The extreme case studies in which the motor must give maximum torques necessary to move upper limbs have been studied.
For example the mass of the robot of Version 3, during the simulations is increased for 158 grams on the arm.

The design of the first and second prototype can be used in the future, with small changes, depending on which motors and harmonic drivers are used. The values gained during measurement of masses and torque for arm and neck / head can be used as a starting point for designs that are similar to our design.

If a feature has been clarified for one version, often it has not been explained for the other version where similar values exist. The main goal was to obtain a design for Archie, which is more suitable and cheaper. The final solution is the third prototype marked by abbreviation V3, which is nominated as design with the best properties.

12.9 Design constraints at prototypes

In the constructed designs, the following conditions were taken into consideration:

- The lowest price possible,
- Lighter mass and
- The same interfaces in the entire body of the robot.

12.10 Description of V1

The first prototype has more advanced shoulder movement; this version enables the robot to move arm in medial rotation. View of the head/neck is approximate to human view, using two types of neck/head; serial and combined. For neck V1, two linear and brushless DC motors have been used. Upper body has the same view and design as the low body. On the entire body of the robot, except for the neck, brushless DC motors are used. Interface is continuation of the lower part (Tab.10-4 and Tab.10-5).

Disadvantages of V1;

- Price is too high (approximately € 20 000)
- Design consists of very small parts, which are difficult for production. Too much time is required to construct the parts of this design.
- Difficulties in assembling and disassembling, especially in very small parts.
- Mass is over 3, 5 kg.
- High consumption of energy (power).
- Motors are required to have high torque, to gets close to maximum of what they can provide.

12.11 Version V2

Design of the upper body is almost the same as that of low body, particularly on the view of the part of hips with shoulder, but with smaller size. Motors and interface are the same in the entire body of the robot. Compared to V1, it has some advantages; the designed parts have larger size and are easier for construction, providing facility in assembling and disassembling.

Disadvantages of V2

- High price, (at least € 18 000)
- Higher mass of approximately over 3.7 kg thus increasing the possibility for lack of stability during fast movements,
- Use of powerful and expensive motors,
- High consumption of batteries

12.12 Version V3

Design of the upper and low body is different, interface is same, and motors are different. Table (Tab.12-6) provides some features of the three versions so that their differences can be seen

The extraordinary low price for the construction of this design (approximately € 5000) is an advantage;

- Very low mass of the upper body, approximately 1.8 kg;
- The number of motors is reduced for three (10 motors), compared to the first and the second prototype.
- Designed parts are easy for production, because they are larger in size and the number of parts is smaller.
- Easy to assemble and disassemble (thus facilitating the work of study during practical experimentations with the robot)
- Dynamixel (RX-64, RX-28) are practical and in a convenient price.
- Calculations and simulations show the good properties and torque of low value.

One of the advantages of the third prototype is its low mass (lower than 2 kilograms) compared to V1 and V2. From this, motors spend less power at V3, while performing the same movements. Naturally the mass of 3, 5 kg to 3,8 kg of the design of prototype (V1 and V2) loads significantly the motors of the lower body thus risking the stability during rapid movement of upper limbs.

12.13 Mass distribution of prototypes

Chapters written above, calculation of torques of every joint is performed, meaning that the recognition of the mass of every link is needed. Advance recognition of the mass of the robot helps to find torque, as to choose motors of a certain power and then find the reduction gear, to give the required torque. In most of the robots of different designs, work is done in teams, addressing every side, necessary to design and in its construction.

Often evaluation of mass distribution on human body is performed to have a similar mass distribution to the body of robot. The height of a human of 180 cm generally corresponds to weight of 75 to 80 kg, while at robot this mass distribution can be followed, but not completely in the same way, because robot differs from the stability of human being in many features. In the design, a particular attention has been paid to the percentage of concentration of mass in the lower part to be higher than in the upper part, consequently the upper part must be constructed with a lighter weight.

The increase of height, the weight decrease starting from height of 84 cm, means that the upper part contains less than 32% of the overall mass. Axis Ox presents height of the robot given in cm (centimetre), division of body has taken place in five segments to indicate the body concentrated weight in the robot body in those heights; (0 to 42) cm, (42 to 84) cm, (84-100) cm, (100-110) cm, (110-126) cm etc. The axis OY presents the weight expressed in kilograms, mainly concentrated in the zones measured by length of the robot. From this approximate measurement, the graph (plot) has been constructed giving a view of mass distribution on robot body (Fig 12-5).

Table 12-4. Some features of V1, V2 and V3

Prototype	***V1***	***V2***	***V3***
Number of actuators	13	13	10
Power consumption of actuators	650 W	650 W	200W
Mass of actuators	2kg	2kg	1.144 kg
Mass of arms and head	3.5 kg	3.7 kg	1.9 kg
Mass of Neck/Head	411g	528.33 g	311g
Static Torque of arm	2.7 Nm	2.2 Nm	1.4 Nm
Surface of design	628034.32mm^2.	507418.26mm^2	377205.23 mm^2
Volume	1276978.42mm^3,	1346043.16mm^3,	914465.16 mm^3,
Mass of arm	700.36g	841.18	675.30 g

In hardware proposal, and during the design stage, features that a robot should have were taken into consideration; including price of equipment, energy consumption in general, memory and power of processors for processing and mass of the robot. Given that robot is a double pendulum, hanging of large mass on the upper part would impact its dynamic stability. Therefore attempts have been made to have the lowest mass possible. The majority of robots attempt to have a pyramid distribution of mass on the body of robot, so that robot mass is concentrated on the lower body. Usually the maximum mass is concentrated in the part of torso, at majority of robots.

For this reason the contact surface of feet to the ground is increased (foot size of Archie; 23 length and 17cm wide), so that higher stability of robot is ensured or the lower part of limbs is built of a material of a higher mass.

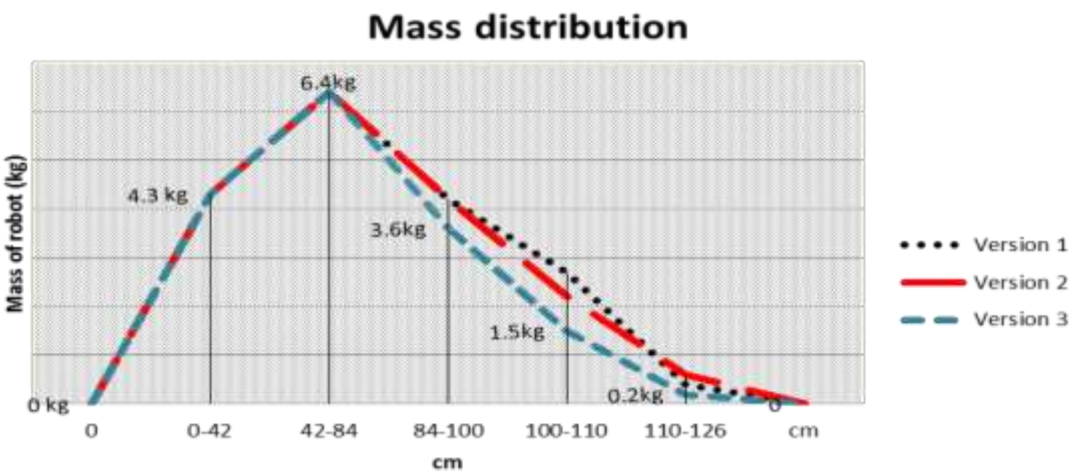


Figure 12-5. Mass distribution

From the mass distribution of the first version and of the second version, an approximately equal distribution is obtained. In the third version the mass has a more pyramidal distribution, given that the upper body is much smaller compared to two other versions.

Hence, it is understood that the third prototype has a higher stability, and proportionately lower consumption of the power. Motors have sufficient power to move the upper body of the robot. Of course, movement of a heavier weight requires more power of and consequently higher consumption of batteries, robot is equipped with. In this aspect the third version has advantages compared to the two other versions.

The graph (plot) shows that mass has been concentrated mainly on the height of the body of the robot from a height of 42 cm to 84 cm, means on the part of torso having approximately the 38% of the mass of the entire robot, whereas the low body contains over 62% of the total of its weight.

Plot shows that prototype three (V3) in height of over 100 cm up to 126 cm has a low weight beginning with weight of 3.6 kg, falling down to 0.2kg. Approximately 30% of the weight is concentrated on the height over 84 cm of the robot.

Leg motors installed at height of 6.2 cm over the feet, during the movement need more energy because they must keep and convey the entire mass of the robot. The higher the motors are located on the body of robot; the lower is their load during their work.

12.14 Peak torques V2 and V3

Table 12-5. Peak torques of Archie major joints V2

Arm	**Torque (Nm)**	**Angular (degree)**
Joint 5 (wrist)	0.053	+/-90
Joint 4 (elbow)	0.728	+/-90
Joint 3 (shoulder)	2.78	+/-90
Neck/Head		
Joint 1 (neck)	0.155	+/-90
Joint 2 (neck)	0.198	+/90
Joint 3 (Head)	0.097	+/-30

Table 12-6. Peak torques of Archie major joints V3

Arm	**Torque (Nm)**	**Angular (degree)**
Joint 1(elbow)	0.233	+/-90
Joint 3 (shoulder)	1.269	+/-90
Joint 4 (shoulder)	1.269	+/-90
Neck/Head	**Torque**	
Joint 1	0.0923	+/-90
Joint 2	0.0894	+/30

12.15 Achievements in this work

This work presents three prototypes designed for the upper body of the robot, which are unique just as the lower body. Mechanical and dynamic calculations were extensively done at prototypes V2 and V3, indicating the characteristics of joint movement. The third prototype is a mechanical structure with a very small mass in comparison to the height of the robot. Design V3 provides the best choice for the stability of the robot, and the motors are not overloaded during their work because of the light weight. In normal conditions they never use the maximum torques they are able to give. Dimensions of the design are in accordance with lower body, where shape and low weight are unique, a feature that other robots do not have, given the height of the robot. Links of the neck are of such length as to ensure a wide work space and to orientate the cameras in all necessary angles in order to take images, looking in vicinity of robot legs. The end effectors (Head/Neck) of V2 and V3 provide large work space and perform soft movement.

Design also provides the most optimal solution between the best possible performance and the lowest price. Some parts may be replaced by plastic material, such as; the forearm part, or the part of the head. Replaced on the platform where cameras are fixed, reducing further the weight. Advantages of the design have been shown also through calculation of torques, indicating quite low values during the analysed movements. A plastic mask can also be tailored for the robot, having the head view, fixing it on the platform. Mechanical structure designed allows with little change to make possible assembling of motors in platform of the head for the cameras to move independently, up/down and left/right. Design is simple and quite practical for a fast construction, and easy for installation and decommissioning when studying the robot.

Majority of robots have different joints such as: spherical, linear, rotational etc. In this robot there were simply used all joints of rotational type. Nowadays there are various designs available which may have similarity to each other. However, size and mass, number of DOF, shape, workspace, simplicity, results following manufacturing and design are unique at Archie. In addition, there are a large number of requests that have been fulfilled having taken them into consideration during the design and construction. All these requests have been the present design, mass distribution and simplicity. Its manufacturing would conclude the project and make Archie complete on its upper body. Design prototype three (V3) is currently under construction.

Novelties achieved by the design include:

- Low price and high performance
- Low weight of upper body
- The shape of the design and dimensions give robot the possibility to make moves of an advanced robot
- Size and Number of DoF, shape, workspace, simplicity and design are unique at Archie
  The design is simple for a construction.

13 Future Work

``Study the past, if you would divine the future``
Confucius

13.1 Proposed Future Works

Construction of biped robot on the whole, contains; the part of the visual system sensors, construction of the neck with three joints, and head with cameras, low body and upper body, systems and equipment of the robot with all the necessary sensors for orientation, balance, and improvement of control. Taking in consideration the advancement of Humanoid robots, there is a need for a new Archie.
Endeavours for advancement of the robot will be divided into two stages;

The first stage;

a) A whole redesign of the electrical architecture. Considering that the electrical part during use and connection of conductors is outdated. This redesign includes; changing of conductors, replacing the controllers for more practical usage during the search, as is the ability of plug in and plug out of the conductors.

b) Equipping the robot with sensors of the force on the feet, gyro sensors, thus increasing stability and control.

The second stage;

a) Construction of a new prototype Archie includes the entire mechanical design, attempting in removal of solidity in joints, and the shape of the skeleton is built by lighter materials, using plastic parts as well. In the new mechanical design of the skeleton of the robot, new electrical parts can be used, compared to the ones used in the first stage.

b) Robot’s body will be built part by part in modules; they will operate separately, and then will be mounted in completeness. This would also facilitate study work and experimental work of every part in particular, but also fixing the defects that would emerge during research work regarding robot.

13.2 Design in the future

Design of back and the hip must undergo some changes, growing proximity with the human movements. The first, at hip part three DC brushed motors should be removed from the design and the brushless DC motors of the hips where low limbs are connected, replacing them with three powerful ones, installed in the shape of a star connection. This would put closer the view of connection to low limbs at the part of the human hips. One motor would have the rotating shaft directed to OZ axis, while two others that will be connected to low limbs of the robot. This would reduce the number of motors at the part of the hips, from 7 to 3 motors (two of them with 3 DOF spherical joints) (Fig 13-1). While half of the upper part of the back, approximately 25 cm from hips, at the spinal cord can have one motor added, with narrow angle of movement, one joint would move the part of shoulder.

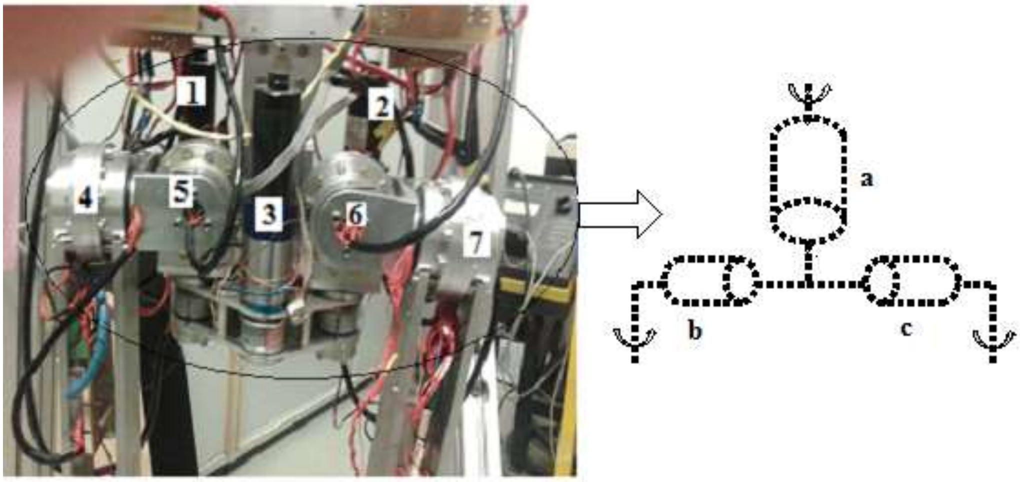


Figure 13-1. Reducing the number of motors

Motor would be the most powerful one, would keep the whole part of the upper body rotating in certain angles. While motors *b* and *c*, would be the motors to move the low limbs.

Some parts may be replaced by plastic material, such as; the forearm part, or the part of the head. Replaced on the platform where cameras are fixed, reducing further the weight. Advantages of the design have been shown also through calculation of torques, indicating quite low values during the analysed movements. A plastic mask can also be tailored for the robot, having the head view, fixing it on the platform of head.

The robot eyes - In future, small motors would be incorporated, and they would act in movement independently of cameras in pan and tilt. Movement of the robot eyes, 3 actuators would be added, they will increase the number of DOF for 3 (the whole body number of DOF 23 till 26 for V3).

Controllers - Number of ELMO motion controllers can be reduced, replacing them with new controllers of a type to enable them to control more motors per controller, and thus the structure of information system would be simplified.

Hands –The part of the hands has not been designed. Construction of hands and completing of the head includes the part over the camera (eyes of the robot), thus, it would make the robot further complete in the future projects.

14 SUMMARY

The study covers a description of the information system, architecture of hardware and software for building biped robot. Parts that constitute the body of the robot, depending on their features, define quality of performance of the robot. In the part of hardware, an important role is played by the interfaces, type and speed of communication of devices between each other that is conducted between the lower and the higher level, and vice versa.

In the first chapter, examples are provided for neck/head of various humanoid robots, made by institutes dealing with the study of Robotics, and companies that produce their own robots. In examples an overview of different forms of neck/head of the robots has been given, and an idea on the design of neck/head has been shared. It also provided discussions about the manner of functioning and adjustment of the upper part, arms and neck/head. In addition to explaining the robot hardware architecture, the software architecture has been described. In this context, in general terms the software architecture of the device was given separately, based on their function; the low level and the main level. With this the description of functioning of the entire information system of the Robot has been included. All are contained in chapters 3 and 4.

Chapter 3 is in particular about vision system. General description of the vision system is given; arrangement, software and hardware. When describing the interface, hardware and software architecture, efforts have been made in creating a study which would be fundamental for Archie. The design of the upper part of the robot, including; neck/head and arms is an effort towards completing robot with the lower and the upper part.

Design is described in detail, with dimensions and forms that are designed in accordance with the lower existing part, in chapters 5,6 and 7. Two design prototypes have been proposed, named as first and second prototype, so that the future designers and scholars can test them further.

The first, second and third prototype have been given for neck/head, and three designs for arms have also been provided. The centres of the mass of links have been given, the mass of links and their dimensions. In all designs, certain limits have been respected as much as possible;

a) To be as practical as possible,

b) Not to affect the general shape of the robot,

c) To have an affordable price as far as possible, especially for third prototype.

d) Mass of both designs to have an unnoticeable difference, so that they have the same dynamic parameters.

In Appendix – A, Appendix B and Appendix C details are given about the design The details allow tests through simulations of kinematics properties and the dynamics of the robot, making various conclusions.

In Appendix E and Appendix D, details are given about mass properties and moment of inertia of prototype one and prototype two.

15 APPENDIX – A

Appendix A - includes all the parts that constitute the design of the neck/head of the first prototype, and the first prototype of arms. In Fig 15-1, the numbers of the parts building the prototype have been presented. Then, each part according to the respective number has been described with dimensions (Tab 15-1) and their view has been presented too.

Notice: It is worth mentioning that the first and the second prototype of the neck/head can be mounted in any prototype of arms and shoulders. So, the prototype of neck/head 2 can be mounted in the first prototype of arms.

15.1 Parts of the first prototype

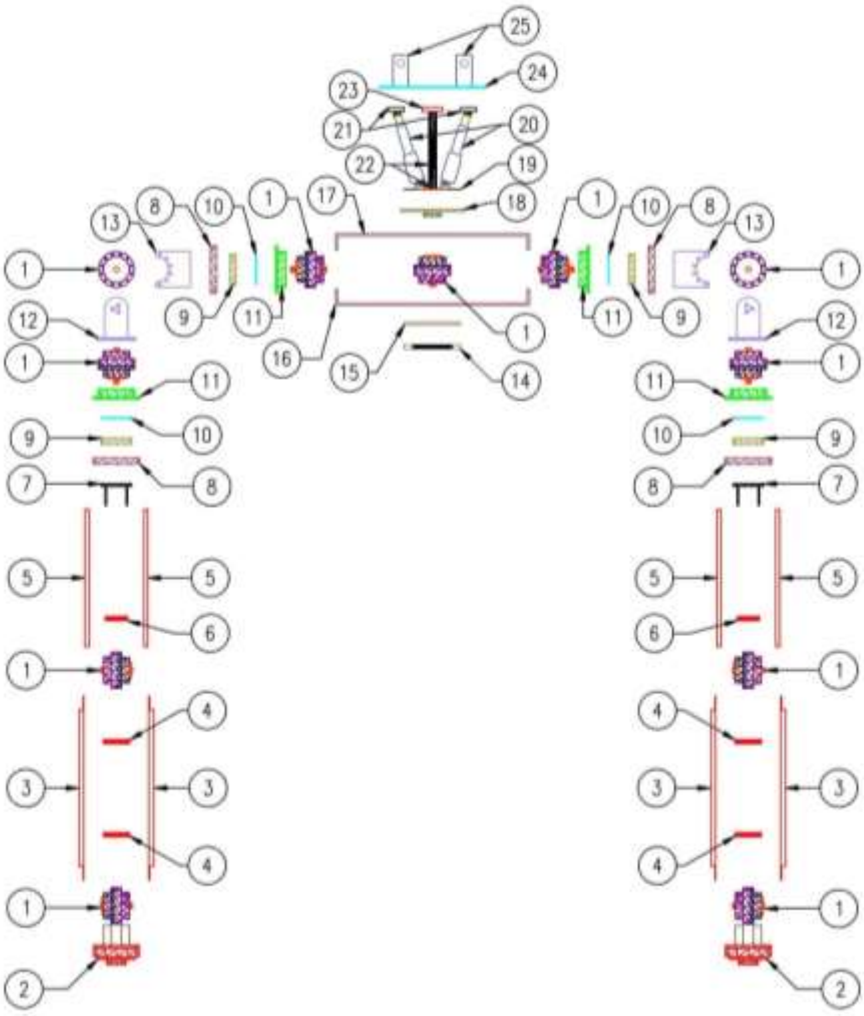
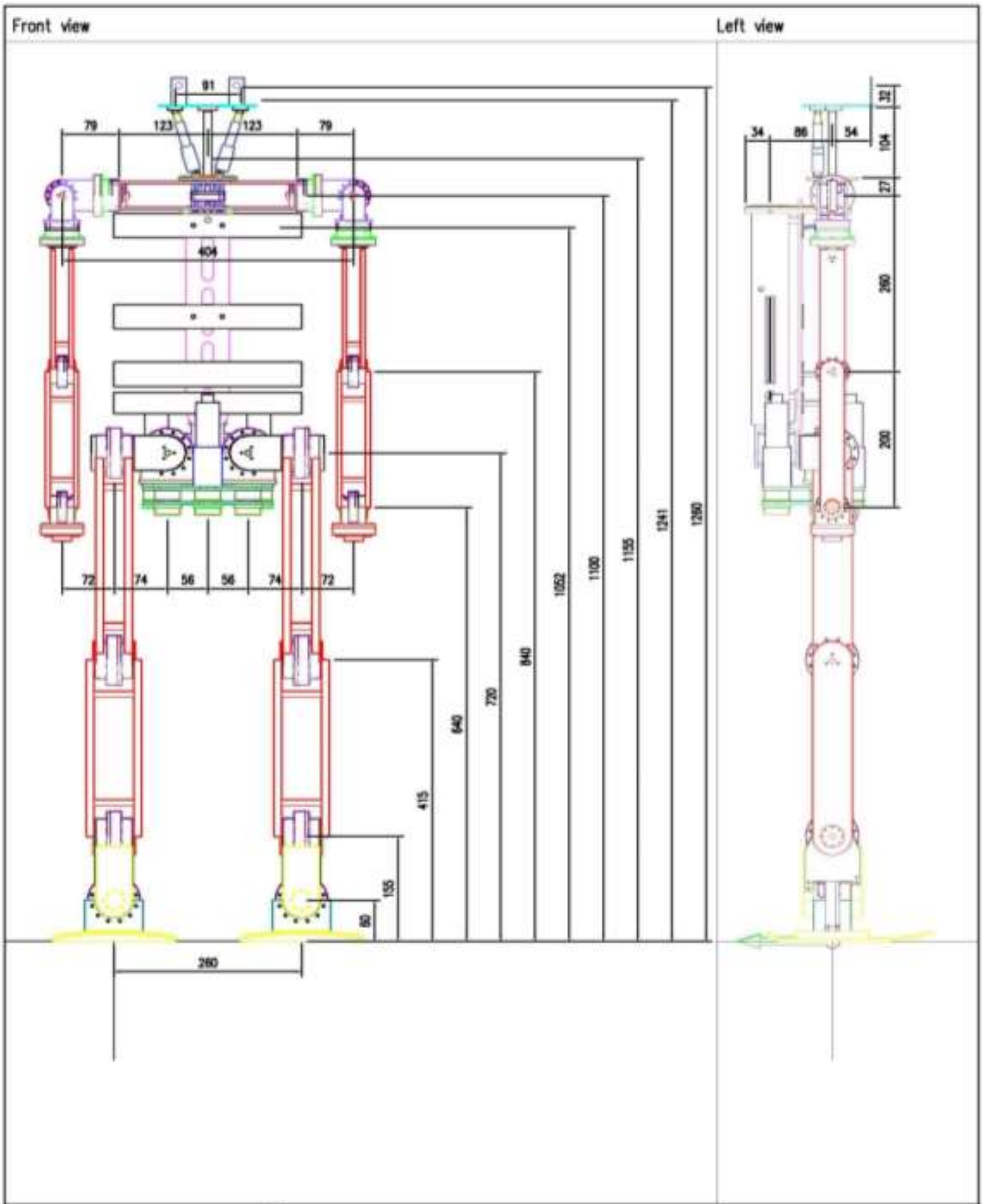


Figure 15-1. Parts of the upper body V1

Table 15-1. Parts of neck/head and arms of Archie:

1-DC brushless motor	12-Actuator Bracket
2-Hand	13-Bracket in shoulder pitch
3- Lower arm aluminium plats	14,15 -Holder sheet
4,6-hold of plats	16,17-Two brackets or chase of upper torso (upper and low chest brackets)
5-Upperarm aluminium plats	18- holder of motor
7-U-Actuator Bracket	19-platform where mini linear motors are fixe
8,11-flang holder	20-Linear actuators with rod
9 - ball bearing	21,23-ball and socket joints
10 plate	24-platform for camera



		TU WIEN - IHRT			
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE Version 2 – Dimensions			
CHECKED BY –	DATE	SIZE A4	DRAWING NUMBER 1001		REV 1
DESIGNED BY –	DATE	SCALE	WEIGHT (kg)		SHEET 1/1

15.2 Linear motors of Neck/Head (first prototype)

Benefits

- Compact miniature size
- Simple control using industry standard interfaces
- Low voltage
- Equal push / pull force
- Easy mounting

Applications

- Robotics
- Consumer appliances
- Toys
- Automotive
- Industrial automation

Miniature Linear Motion Series • **L12**

Firgelli Technologies' unique line of Miniature Linear Actuators enables a new generation of motion-enabled product designs, with capabilities that have never before been combined in a device of this size. These small linear actuators are a superior alternative to designing with awkward gears, motors, servos and linkages.

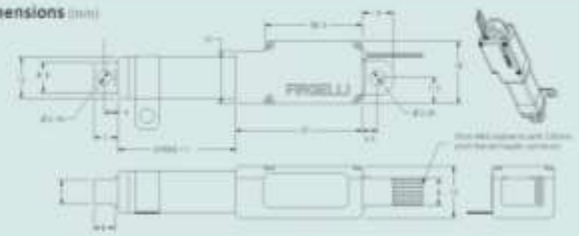
Firgelli's L series of micro linear actuators combine the best features of our existing micro actuator families into a highly flexible, configurable and compact platform with an optional sophisticated on-board microcontroller. The first member of the L series, the L12, is an axial design with a powerful drivetrain and a rectangular cross section for increased rigidity. But by far the most attractive feature of this actuator is the broad spectrum of available configurations.

L12 Specifications

Gearing Option	50	100		210
Peak Power Point [1]	12 N @ 11 mm/s	23 N @ 6 mm/s		45 N @ 2.5 mm/s
Peak Efficiency Point	6 N @ 16 mm/s	12 N @ 8 mm/s		18 N @ 4 mm/s
Max Speed (no load)	23 mm/s	12 mm/s		5 mm/s
Backdrive Force [2]	43 N	80 N		150 N
Stroke Option	**10 mm**	**30 mm**	**50 mm**	**100 mm**
Weight	28 g	34 g	40 g	56 g
Positional Accuracy	0.1 mm	0.2 mm	0.2 mm	0.3 mm
Max Side Force (fully extended)	50 N	40 N	30 N	15 N
Mechanical Backlash	0.1 mm			
Feedback Potentiometer	2.75 kΩ/mm ± 30%, 1% linearity			
Duty Cycle	20 %			
Lifetime	1000 hours at rated duty cycle			
Operating Temperature	-10°C to +50°C			
Storage Temperature	-30°C to +70°C			
Ingress Protection Rating	IP-54			
Audible Noise	55 dB at 45 cm			
Stall Current	450 mA at 5 V & 6 V, 200 mA at 12 V			

[1] 1 N (Newton) = 0.225 lb. (pound-force)
[2] a powered-off actuator will statically hold a force up to the Backdrive Force

Dimensions (mm)



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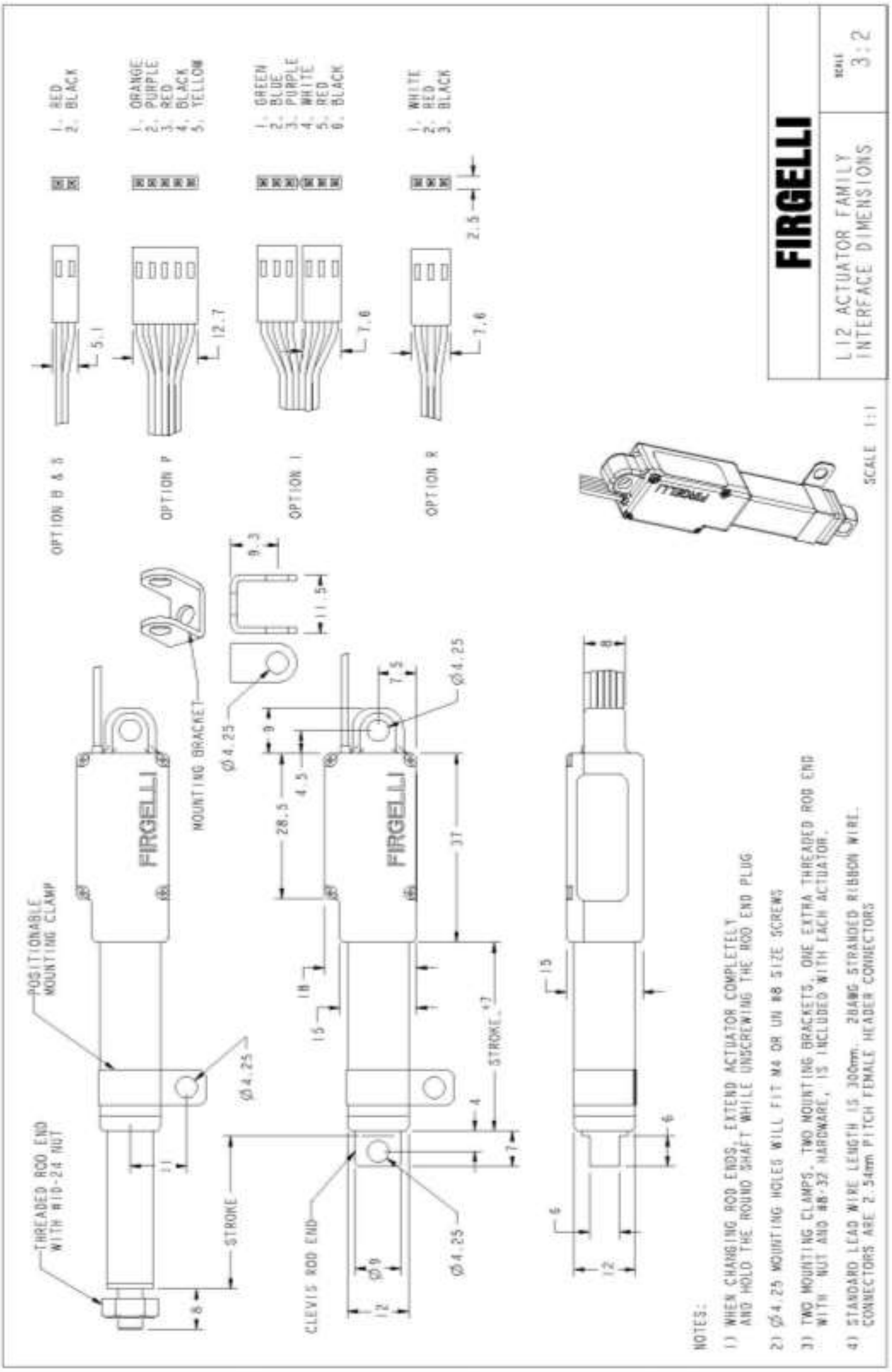
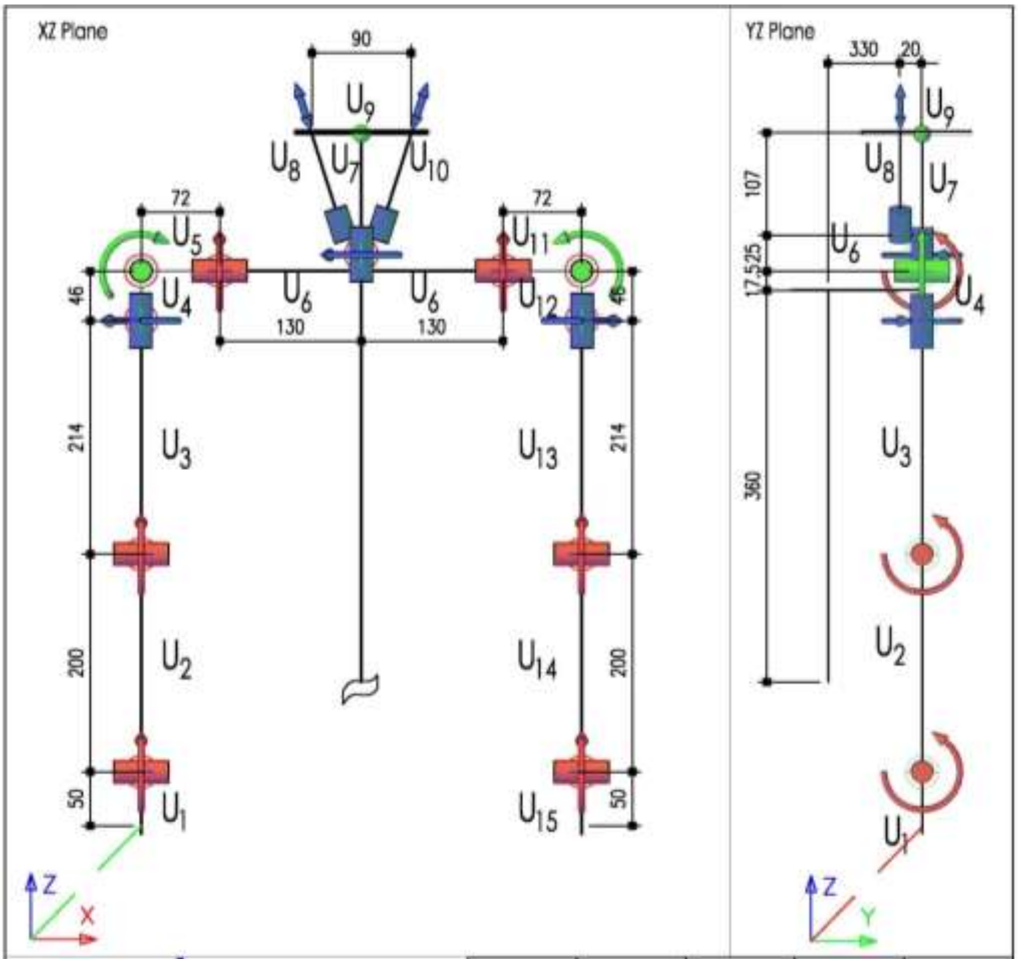
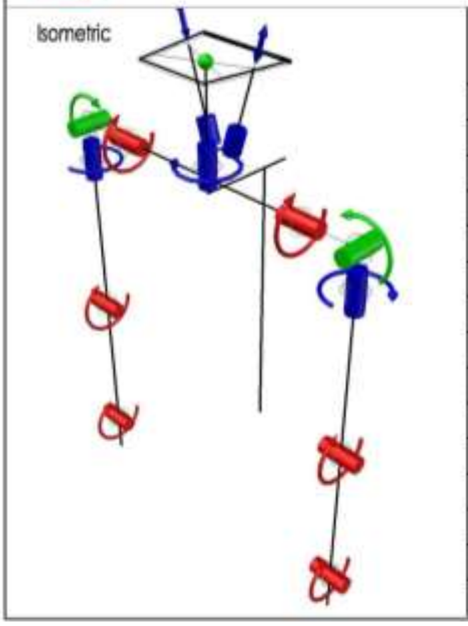
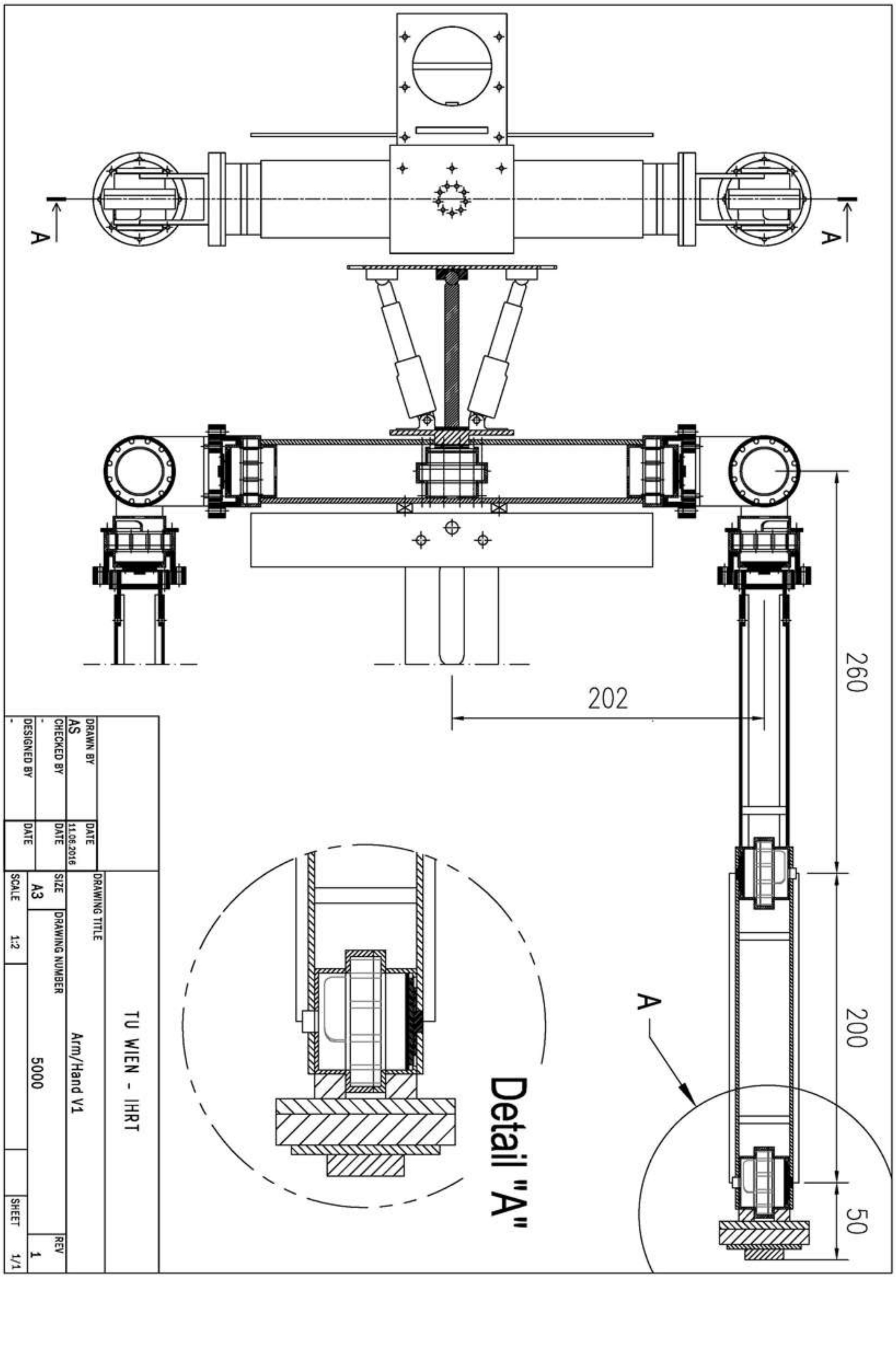
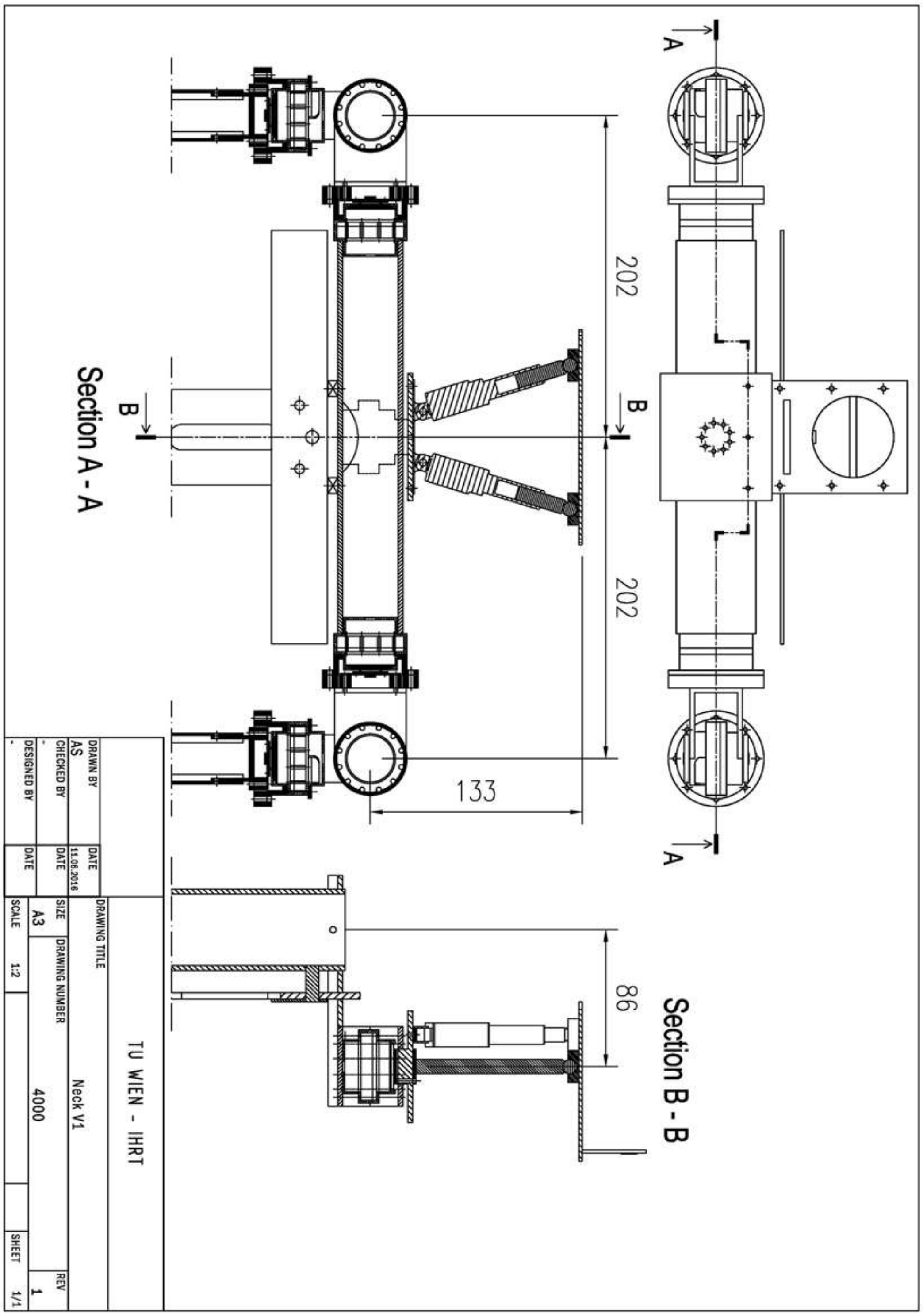

FIRGELLI
L12 ACTUATOR FAMILY
INTERFACE DIMENSIONS
SCALE 3:2
OPTION B & S
1. RED
2. BLACK
OPTION P
1. ORANGE
2. PURPLE
3. RED
4. BLACK
5. YELLOW
OPTION I
1. GREEN
2. BLUE
3. PURPLE
4. WHITE
5. RED
6. BLACK
OPTION R
1. WHITE
2. RED
3. BLACK
THREADED ROD END WITH #10-24 NUT
POSITIONABLE MOUNTING CLAMP
MOUNTING BRACKET
CLEVIS ROD END
STROKE
SCALE 1:1
NOTES:
1) WHEN CHANGING ROD ENDS, EXTEND ACTUATOR COMPLETELY AND HOLD THE ROUND SHAFT WHILE UNSCREWING THE ROD END PLUG
2) Ø4.25 MOUNTING HOLES WILL FIT M4 OR UN #8 SIZE SCREWS
3) TWO MOUNTING CLAMPS, TWO MOUNTING BRACKETS, ONE EXTRA THREADED ROD END WITH NUT AND #8-32 HARDWARE, IS INCLUDED WITH EACH ACTUATOR.
4) STANDARD LEAD WIRE LENGTH IS 300mm. 28AWG STRANDED RIBBON WIRE. CONNECTORS ARE 2.54mm PITCH FEMALE HEADER CONNECTORS



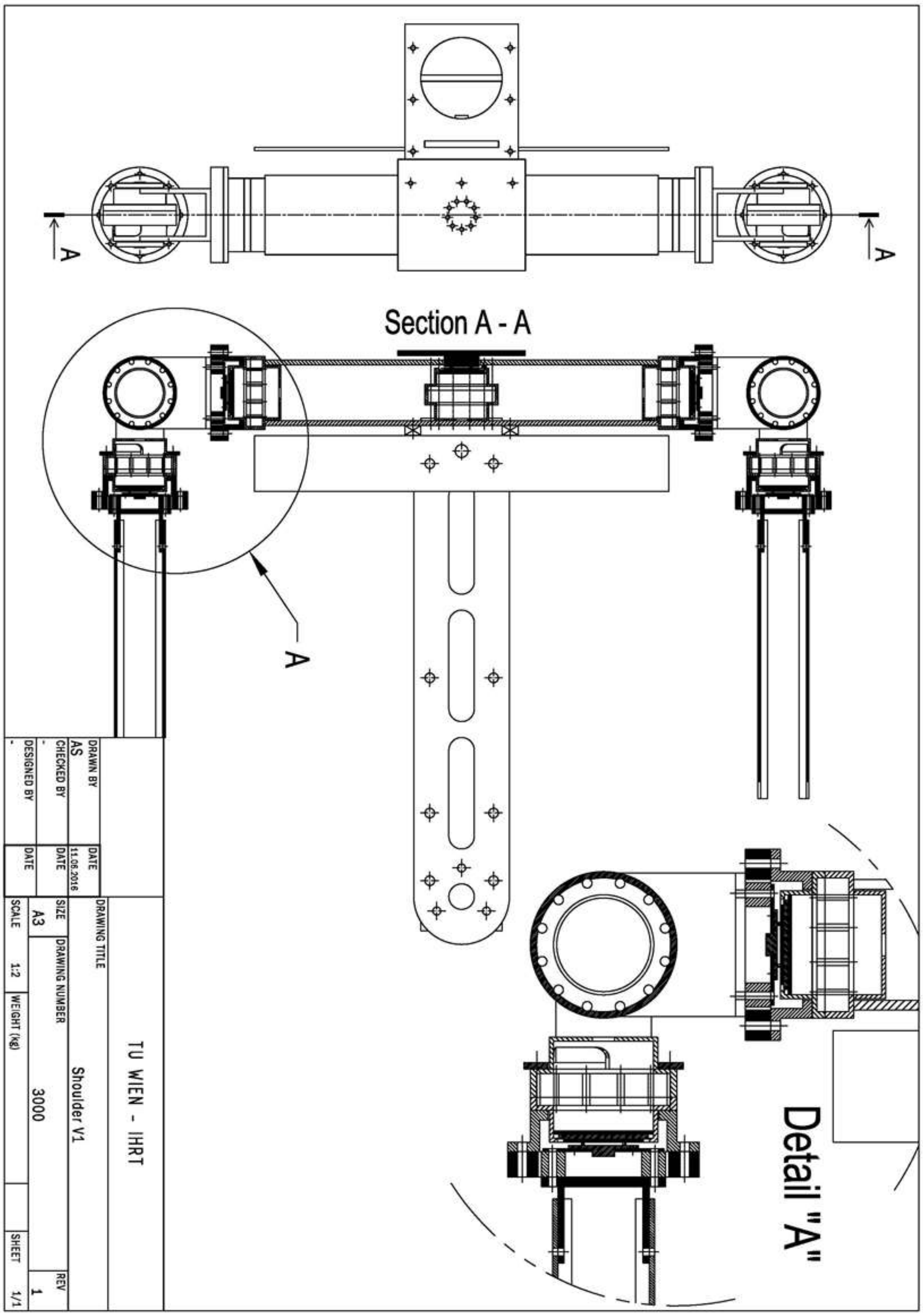


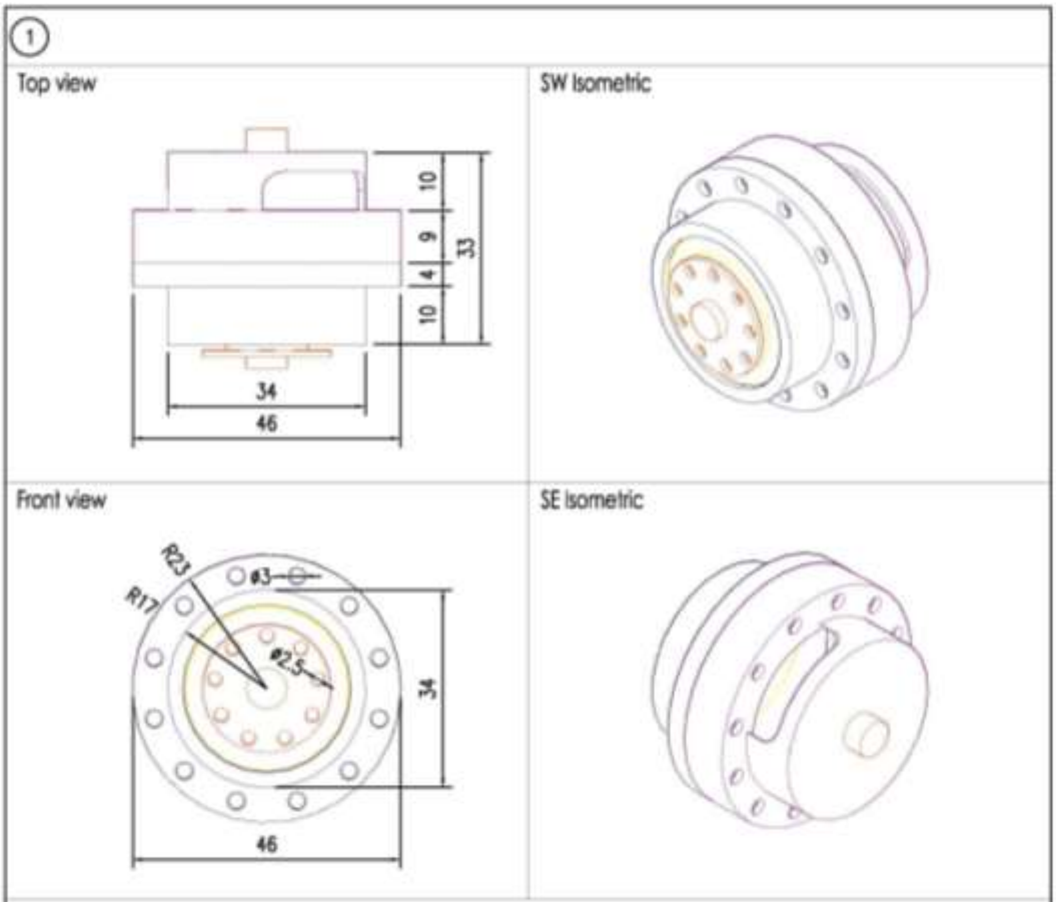
Link Name	Mass (gr)	Center of mass X	Center of mass Y	Center of mass Z
U1	255	0	0	25
U2	228	0	0	150
U3	292	0	0	414
U4	198	0	0	487
U5	282	45	0	510
U6	637	202	−15	505
U7	59	202	−10	540
U8	34	171	−20	586
U9	88	202	0	640
U10	34	233	−20	586
U11	282	359	0	510
U12	198	404	0	487
U13	292	404	0	414
U14	228	404	0	150
U15	255	404	0	25


A
A
260
202
200
50
A
Detail "A"
DRAWN BY
AS
DATE
11.06.2016
CHECKED BY
DATE
DESIGNED BY
DATE
DRAWING TITLE
TU WIEN - IHRT
Arm/Hand V1
SIZE
A3
DRAWING NUMBER
5000
REV
1
SCALE
1:2
SHEET
1/1



A
A
B
B
202
202
133
86
Section A - A
Section B - B
TU WIEN - IHRT
DRAWN BY
AS
DATE
11.06.2016
CHECKED BY
-
DATE
DESIGNED BY
-
DATE
DRAWING TITLE
Neck V1
SIZE
A3
DRAWING NUMBER
4000
REV
1
SCALE
1:2
SHEET
1/1


A
A
Section A - A
A
Detail "A"
DRAWN BY
AS
CHECKED BY
-
DESIGNED BY
-
DATE
11.06.2016
DATE
DATE
DRAWING TITLE
Shoulder V1
TU WIEN - IHRT
SIZE
A3
DRAWING NUMBER
3000
REV
1
SCALE
1:2
WEIGHT (kg)
SHEET
1/1



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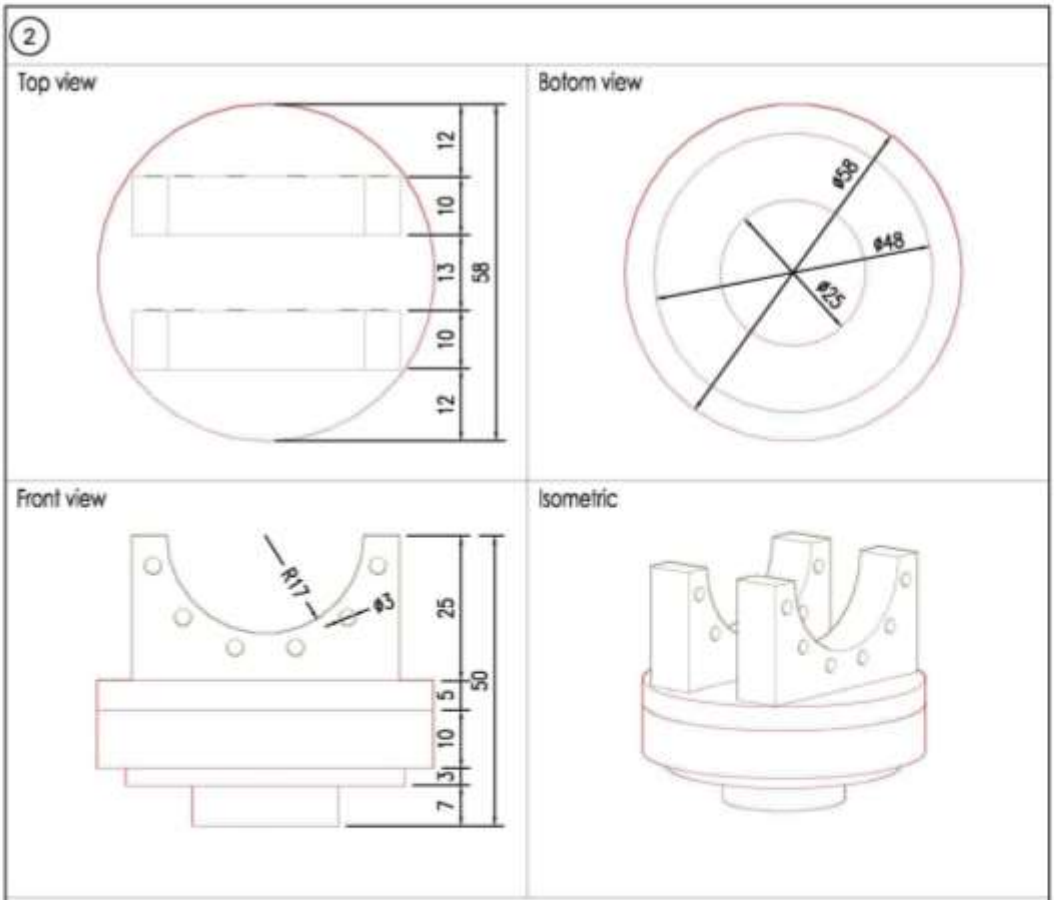
DESIGNED BY -	DATE	SCALE 1:1	WEIGHT (kg)	-		SHEET	1/13



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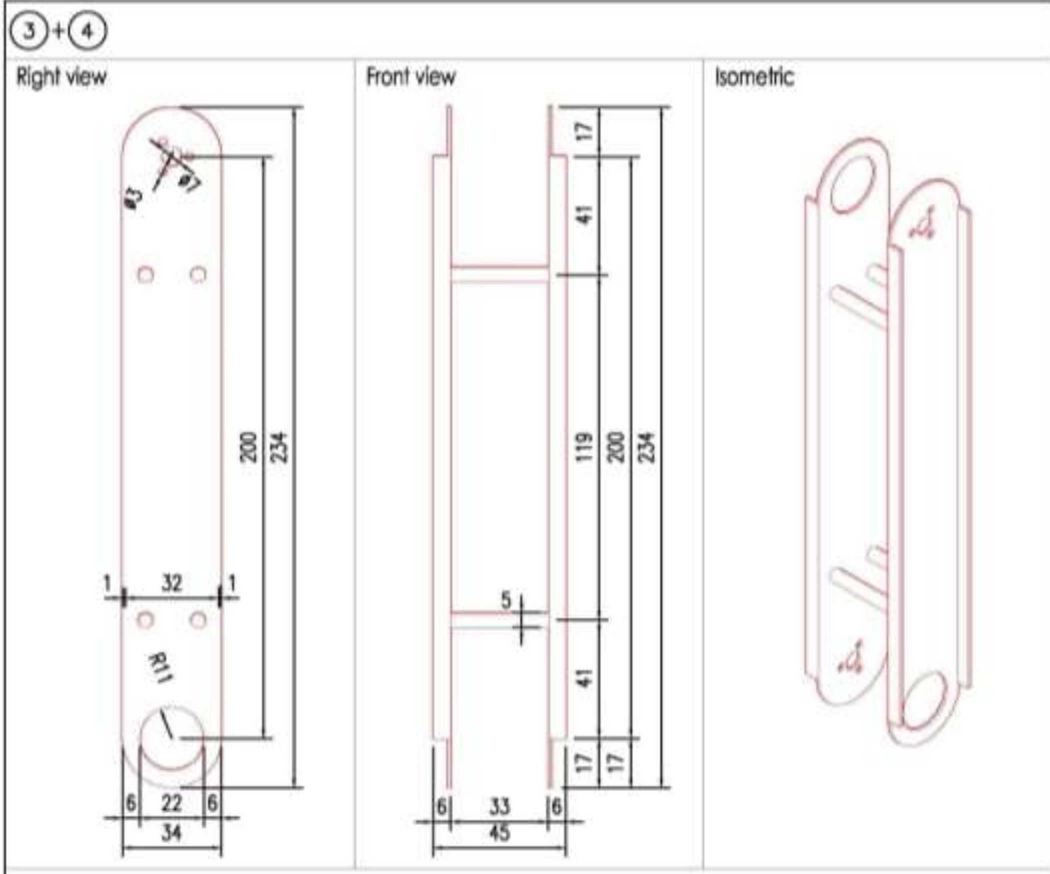
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-		SHEET	2/13	



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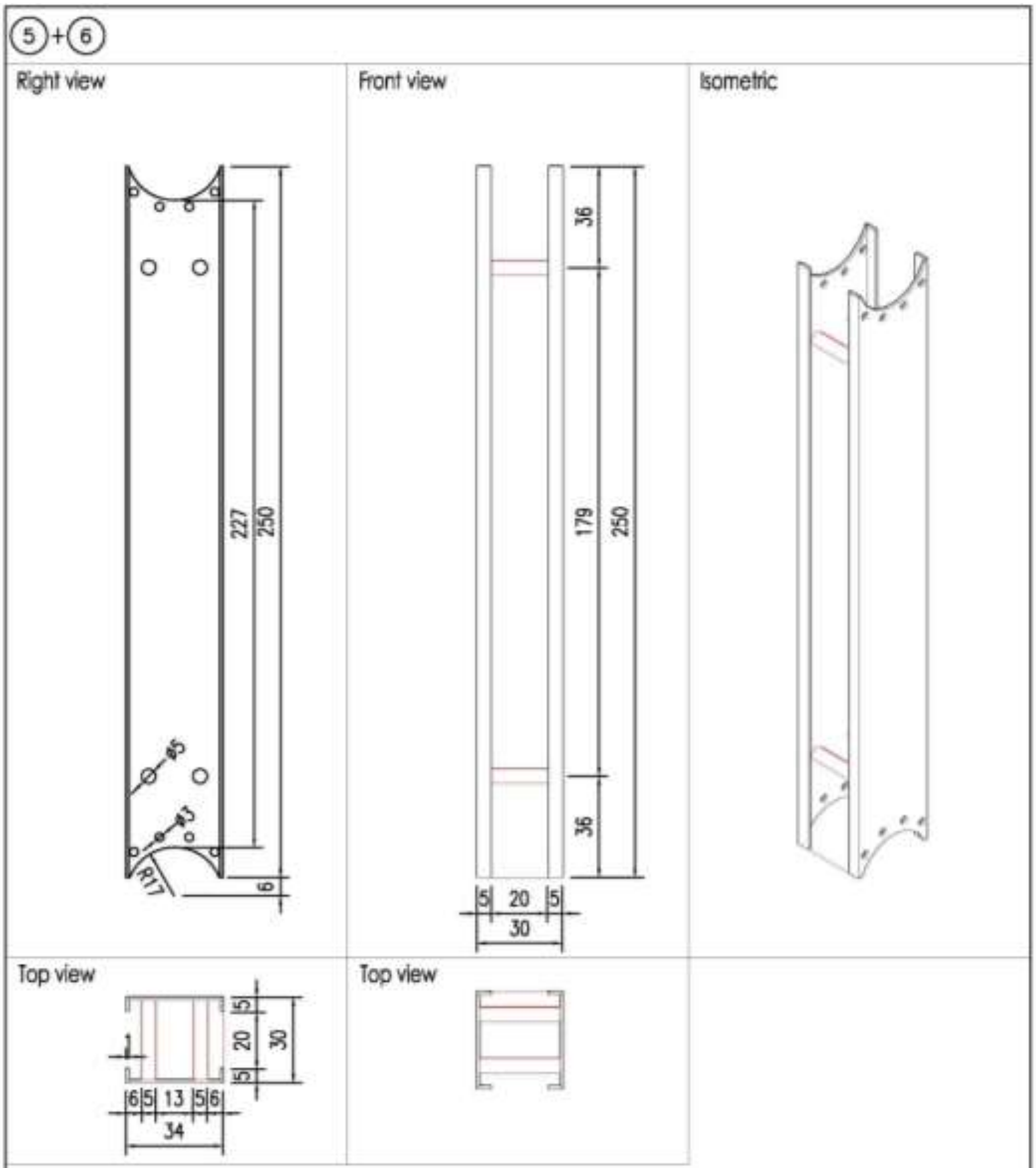
DESIGNED BY -	DATE	SCALE 1:1 · WEIGHT (kg) - · SHEET 3/13



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DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Upperarm aluminium plates & holding pins					
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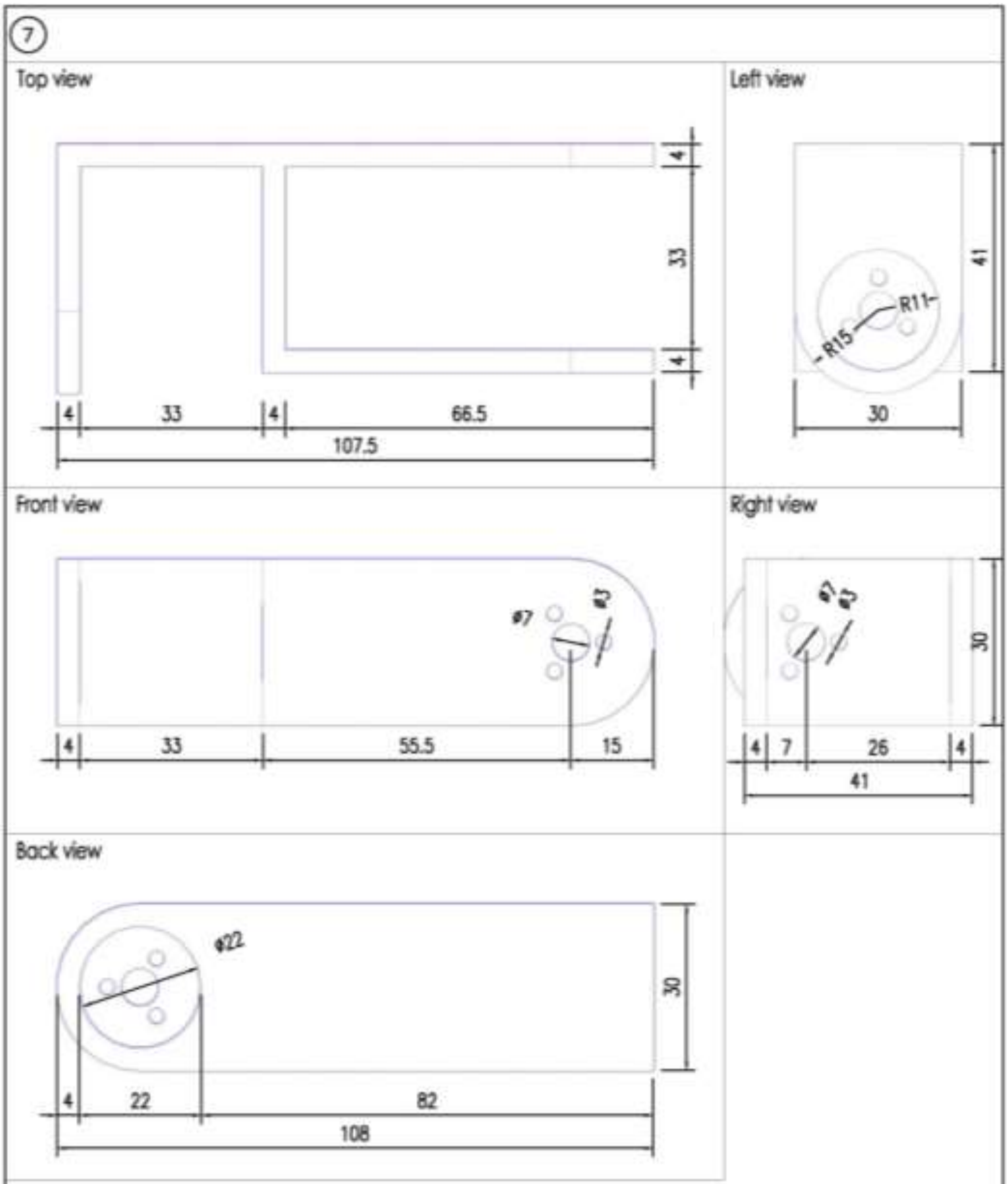
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	4/13



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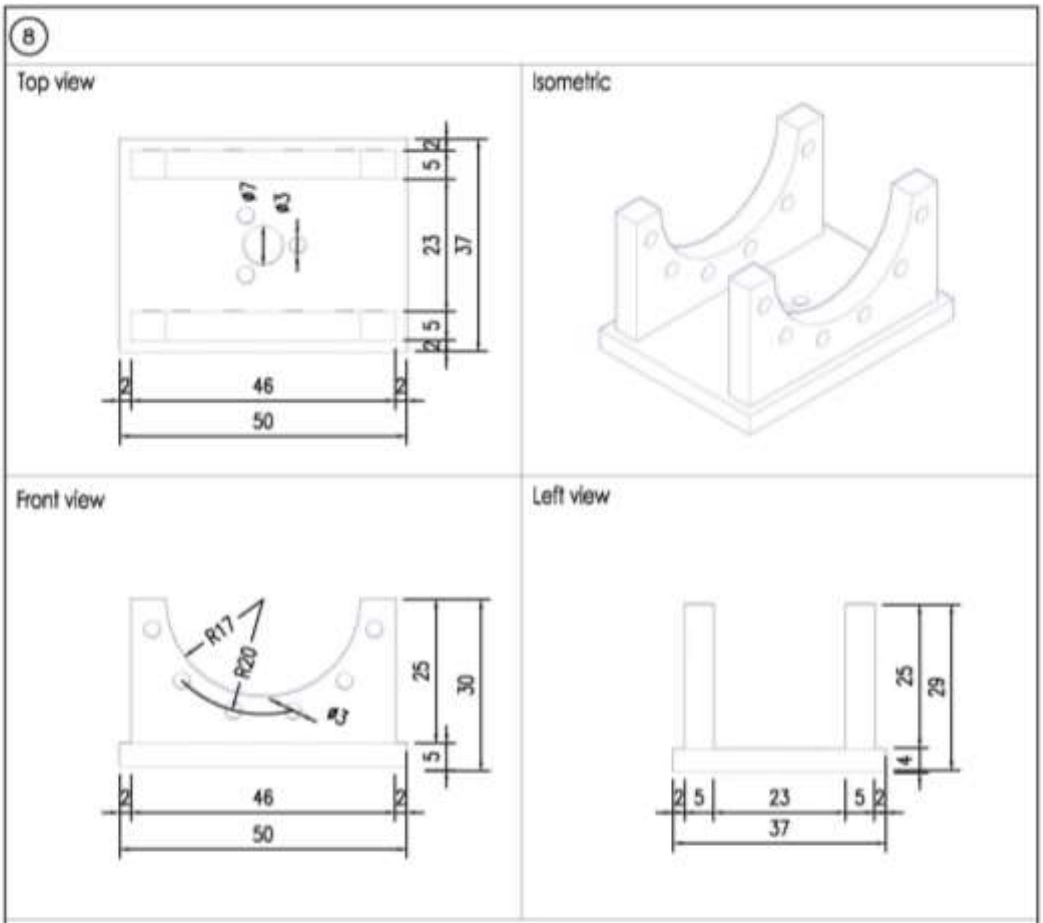
DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Shoulder/Arm joint connector
CHECKED BY -	DATE	SIZE A4 / DRAWING NUMBER 2005 / REV 1
DESIGNED BY -	DATE	SCALE 1:1 / WEIGHT (kg) - / SHEET 5/13



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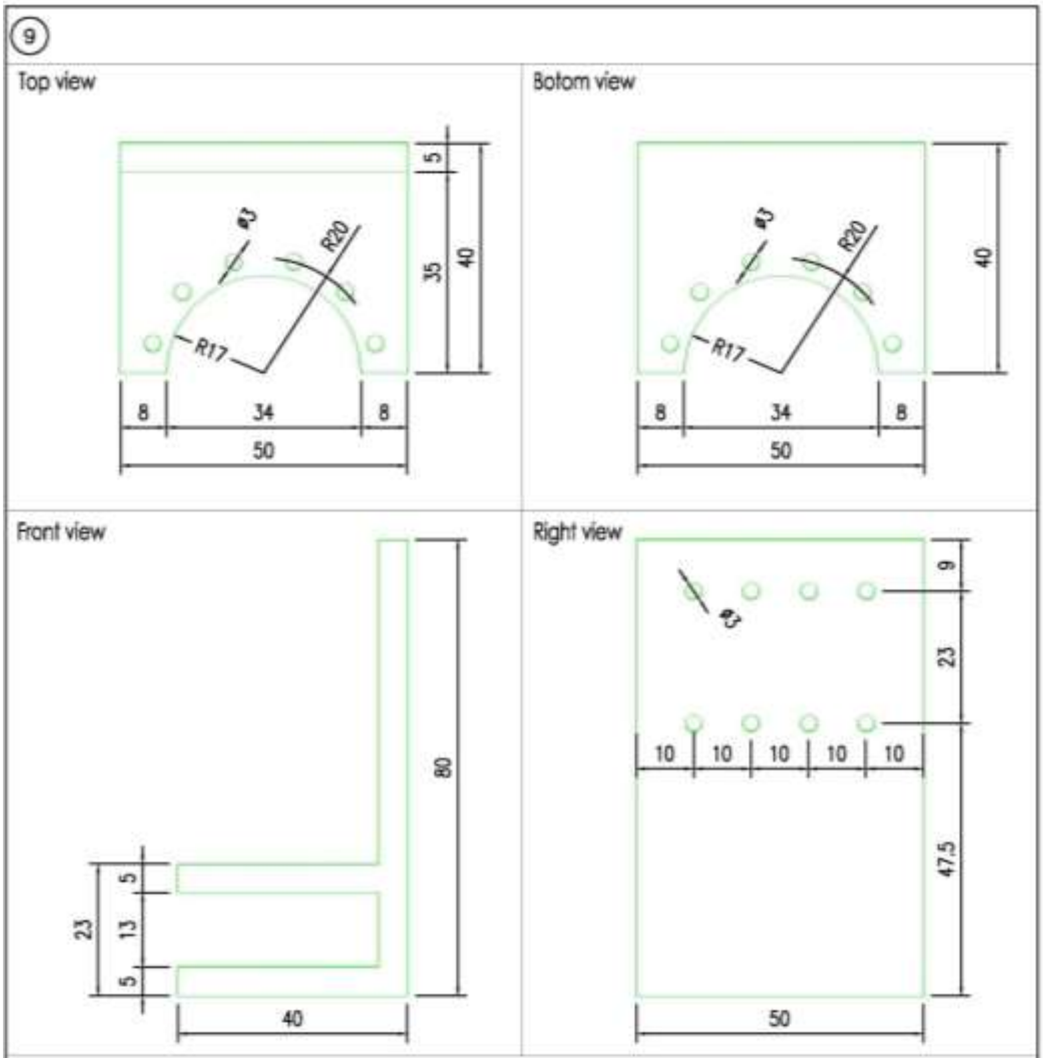

		TU WIEN - IHRT						
DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Shoulder/Neck joint connector						
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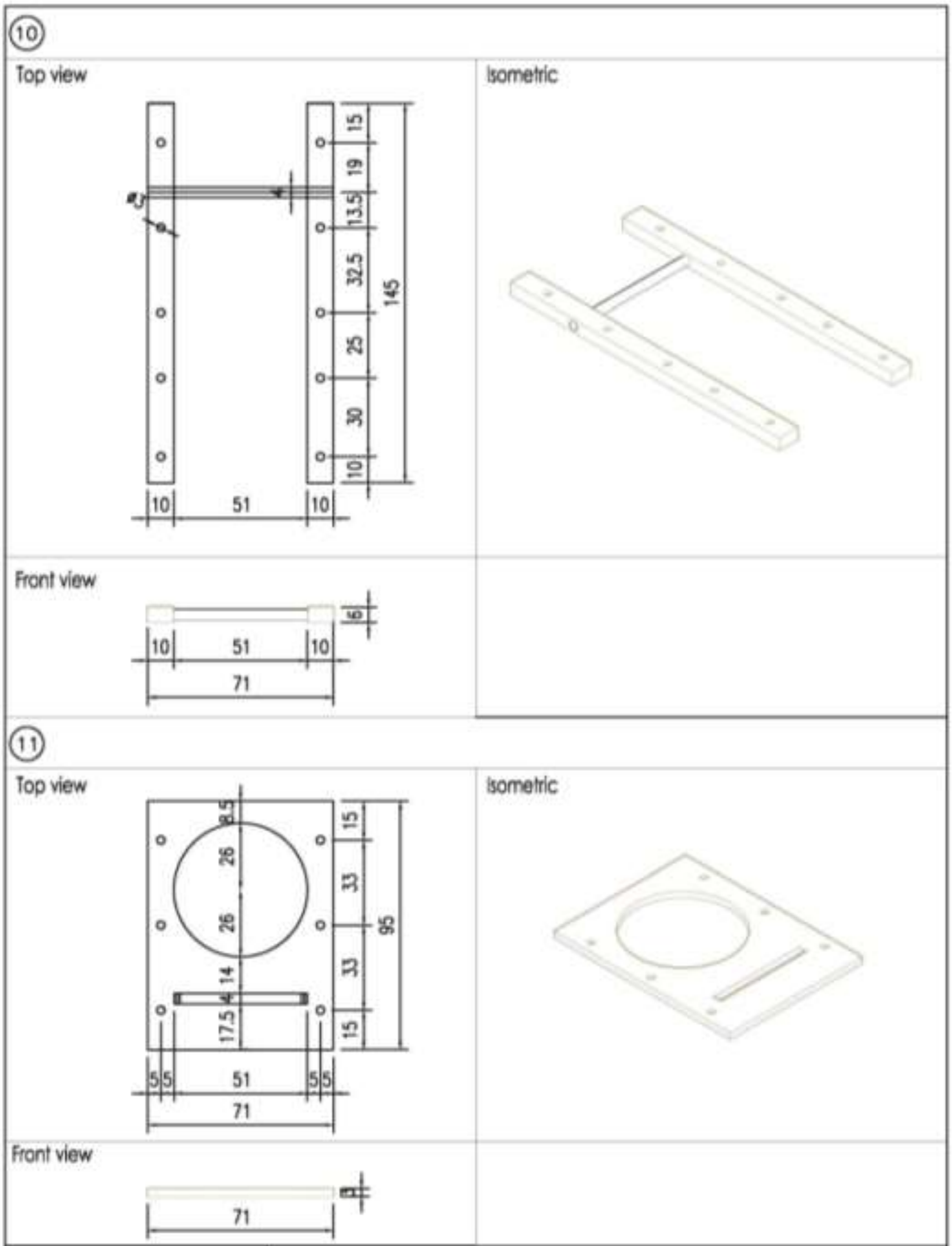
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-		SHEET	7/13



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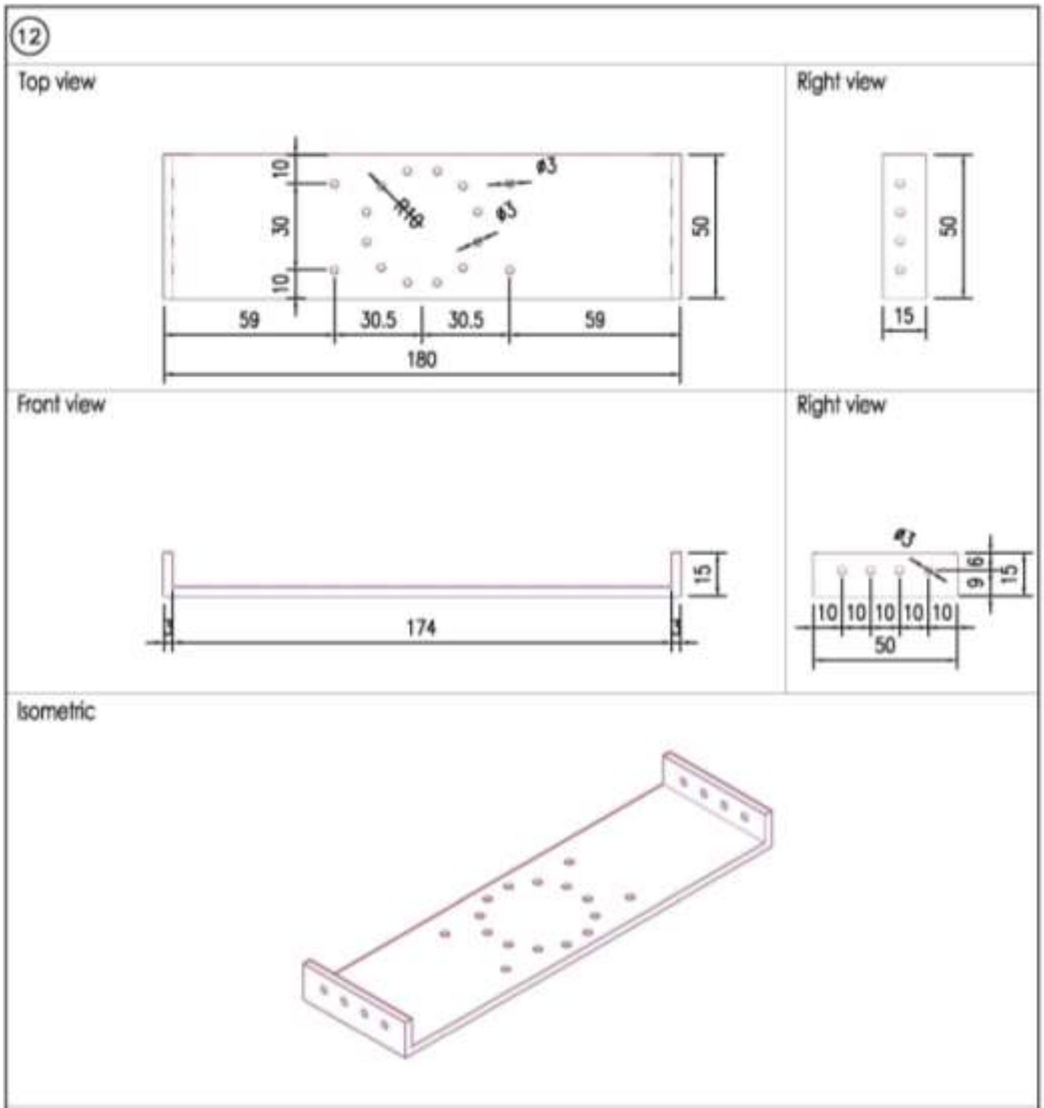
DESIGNED BY -	DATE	SCALE 1:1	WEIGHT (kg) -		SHEET	8/13



TU WIEN - IHRT

DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Lower shoulder bracket					
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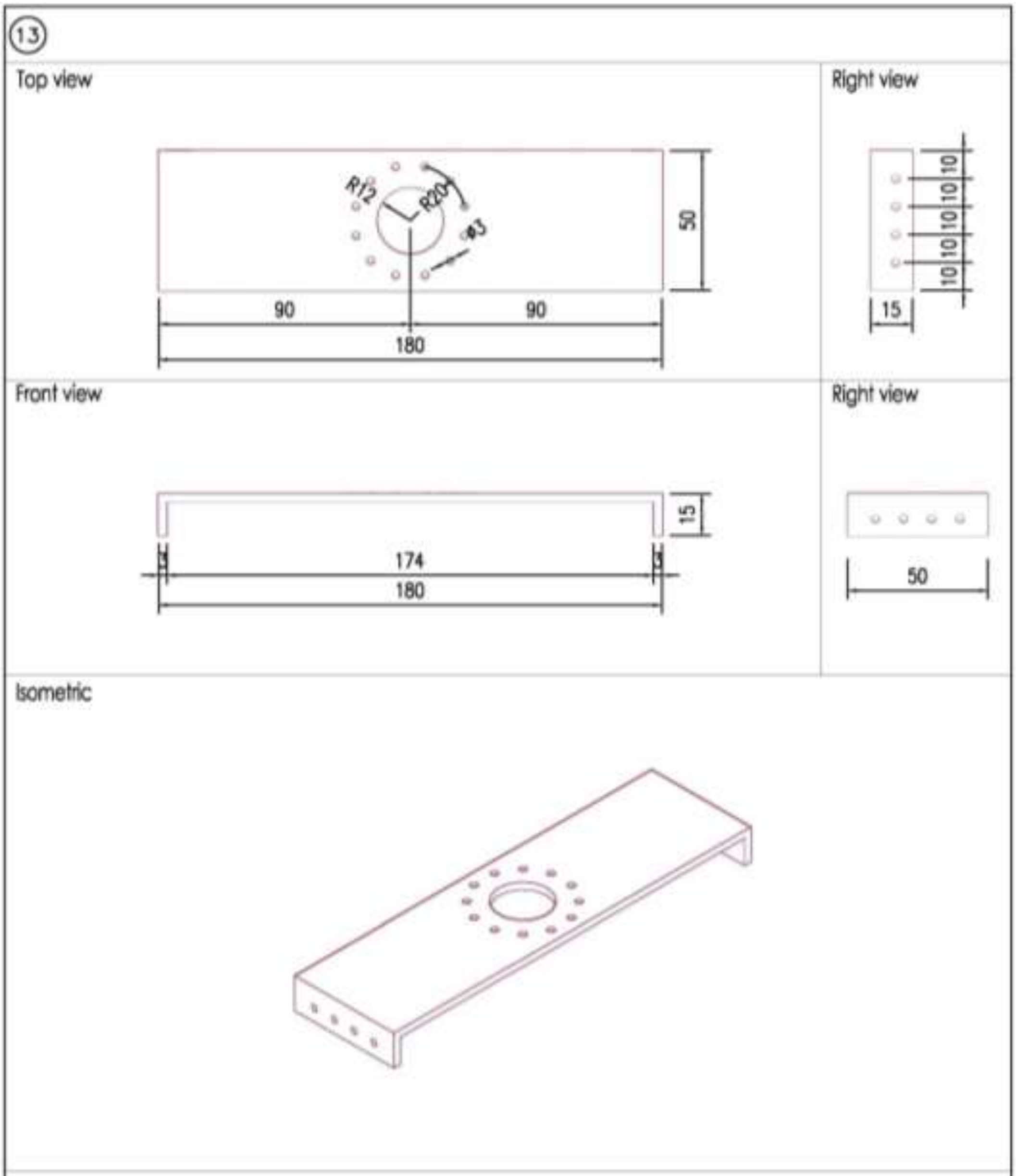
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-		SHEET 9/13



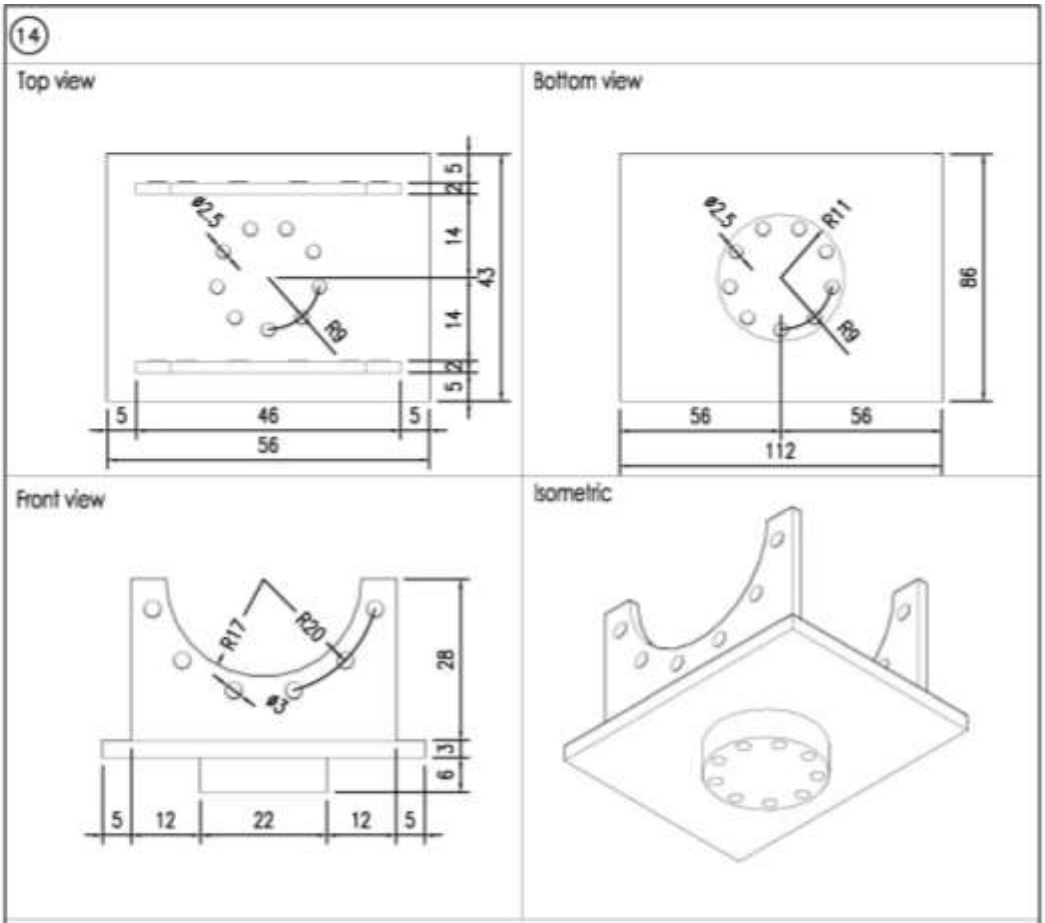
TU WIEN - IHRT

DRAWN BY: AS
DATE: 22.02.2016
CHECKED BY: -
DATE:
DESIGNED BY: -
DATE:

DRAWING TITLE: Upper shoulder bracket

SIZE: A4
DRAWING NUMBER: 2010
REV: 1

SCALE: 1:1
WEIGHT (kg): -
SHEET: 10/13



TU WIEN - IHRT

DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Holder of neck DC motor					
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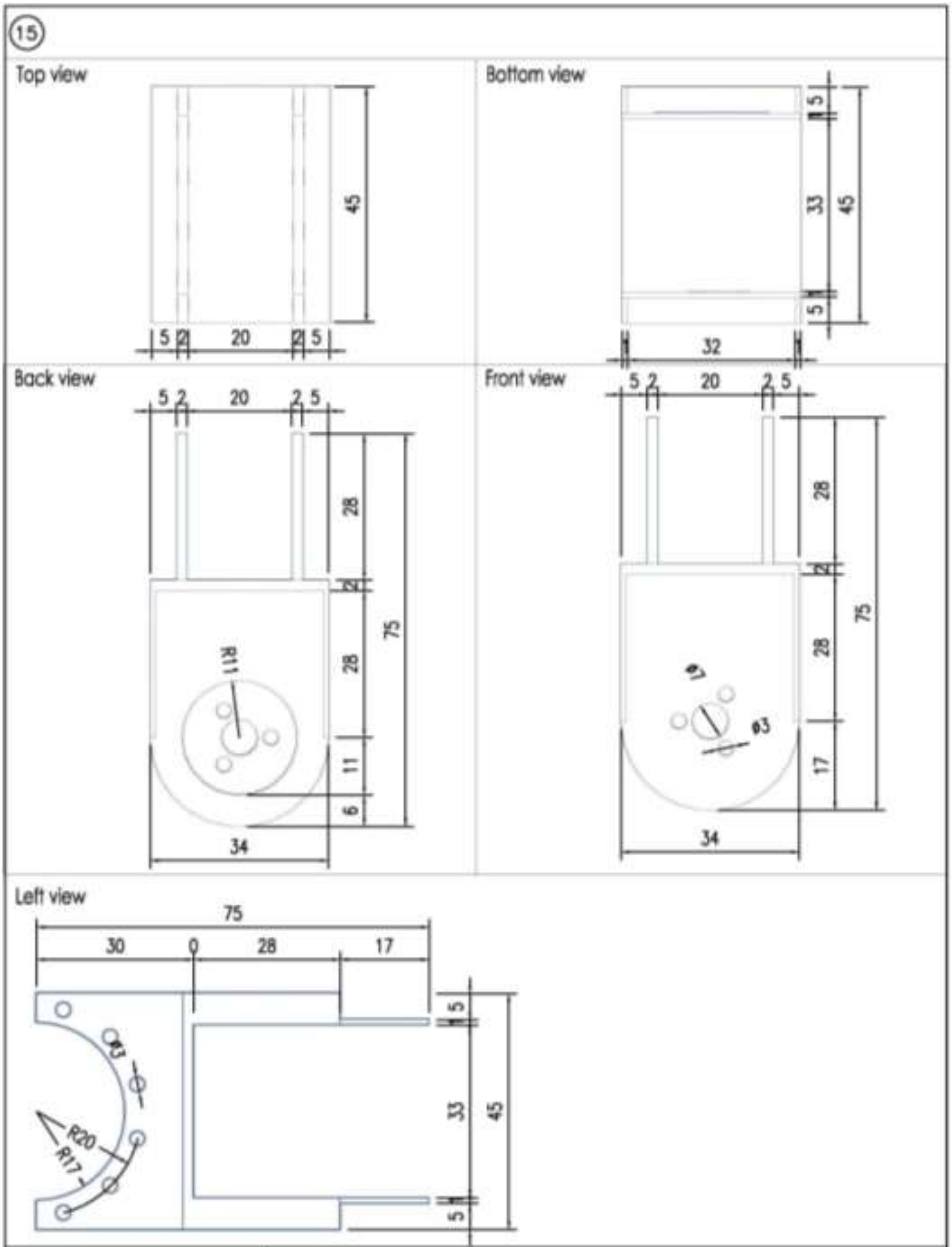
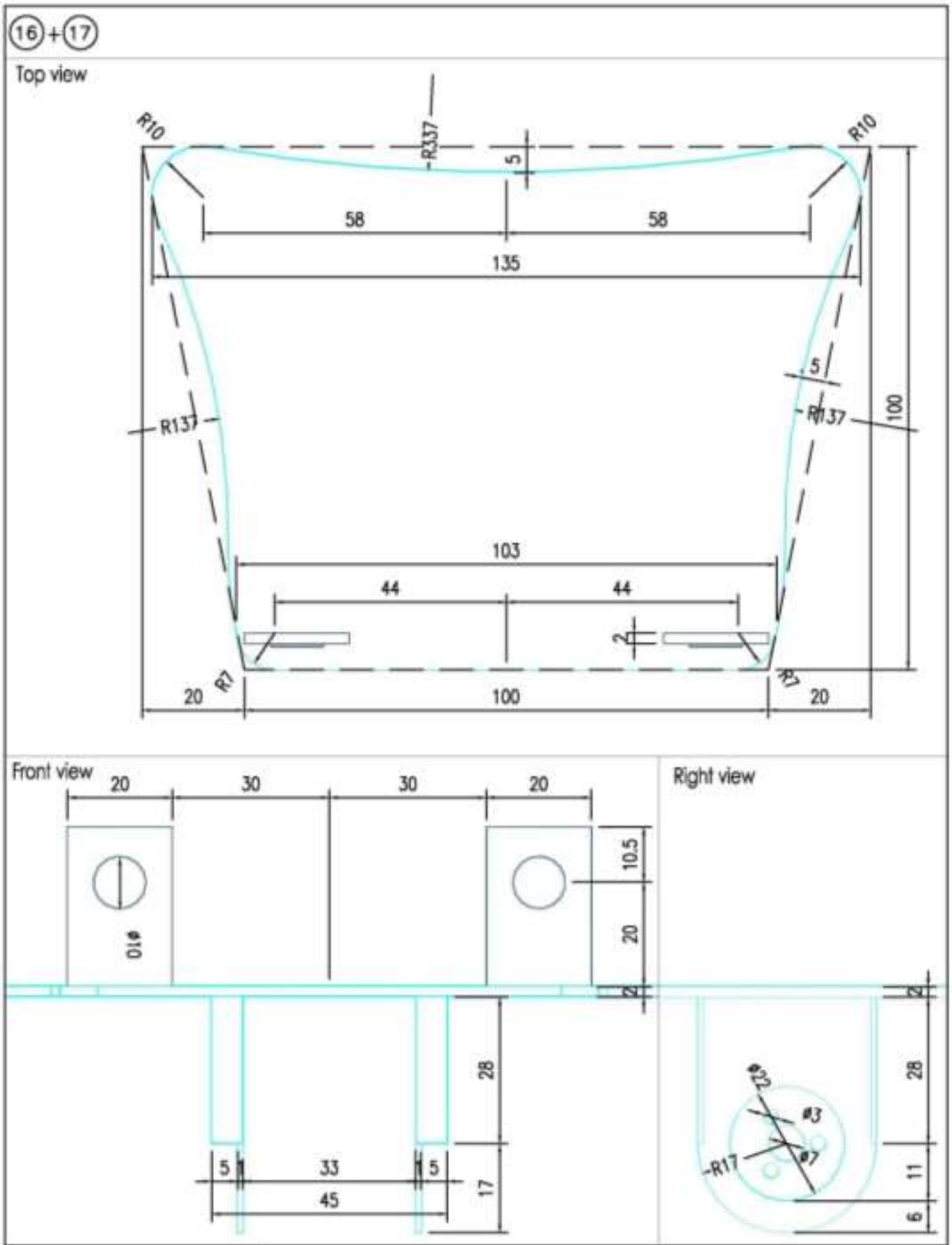
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	11/13



		TU WIEN - IHRT					
DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Holder of linear actuators					
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 2012				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	12/13



TU WIEN - IHRT

DRAWN BY: AS | DATE: 22.02.2016

CHECKED BY: - | DATE:

DESIGNED BY: - | DATE:

DRAWING TITLE: Platform for fixed cameras

SIZE: A4 | DRAWING NUMBER: 2013 | REV: 1

SCALE: 1:1 | WEIGHT (kg): - | SHEET: 13/13

16 APPENDIX – B

Appendix B - includes all the parts that constitute the design of the neck/head of the second prototype (V2), and the second prototype of arms. In figure (Fig 16-1), the numbers of the parts building the prototype have been presented. Then, each part according to the respective number has been described with dimensions and their view has been presented too.

16.1 The dimensions of design V2

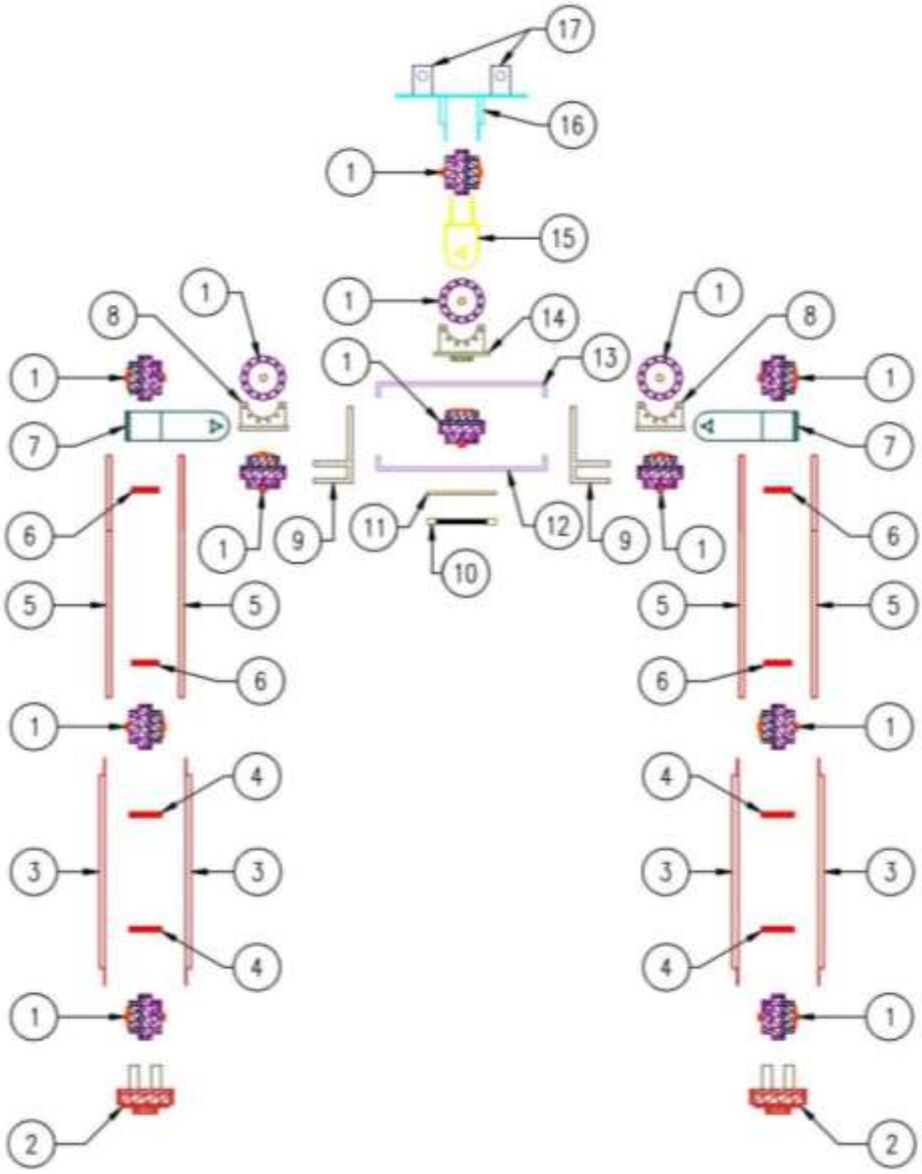
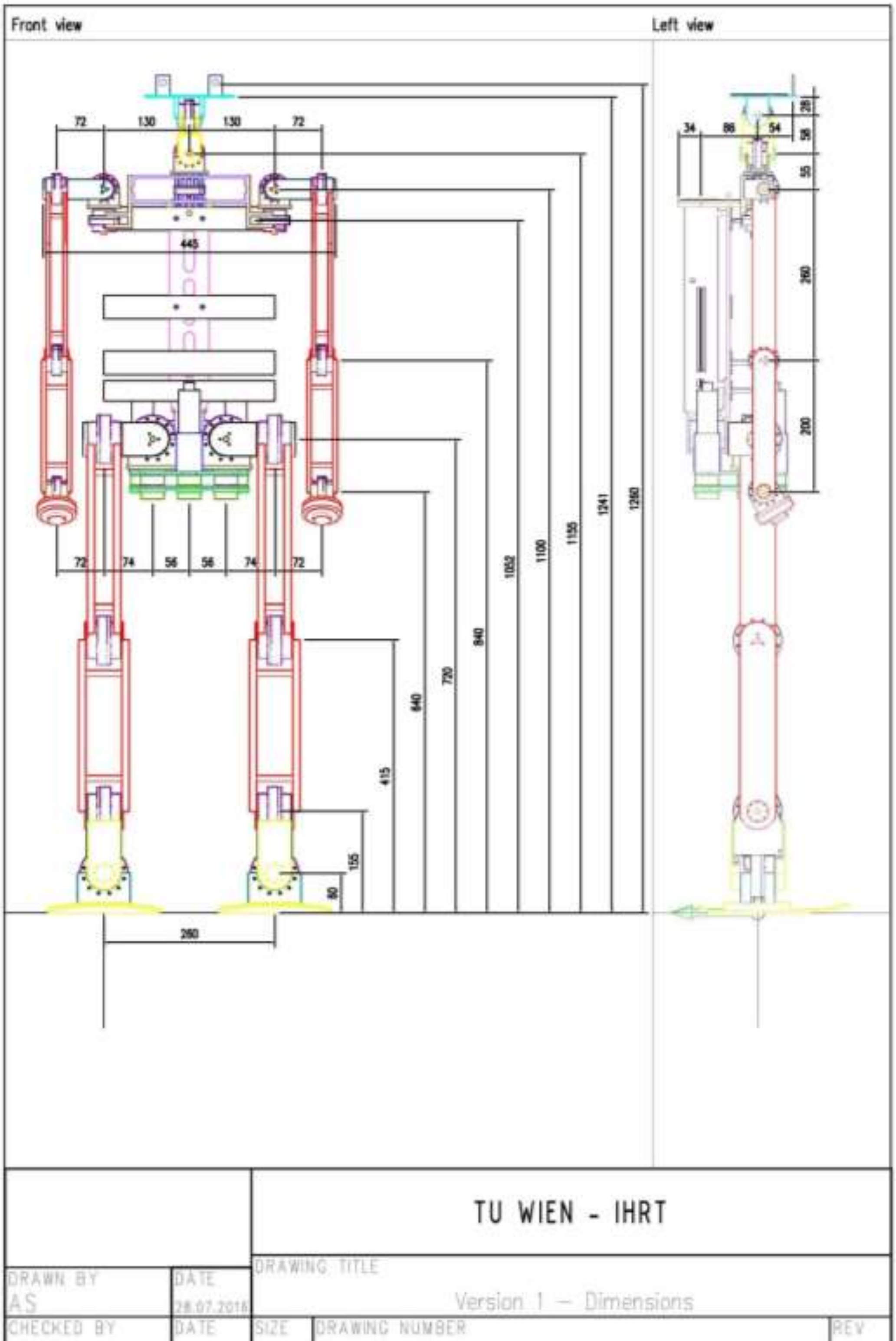
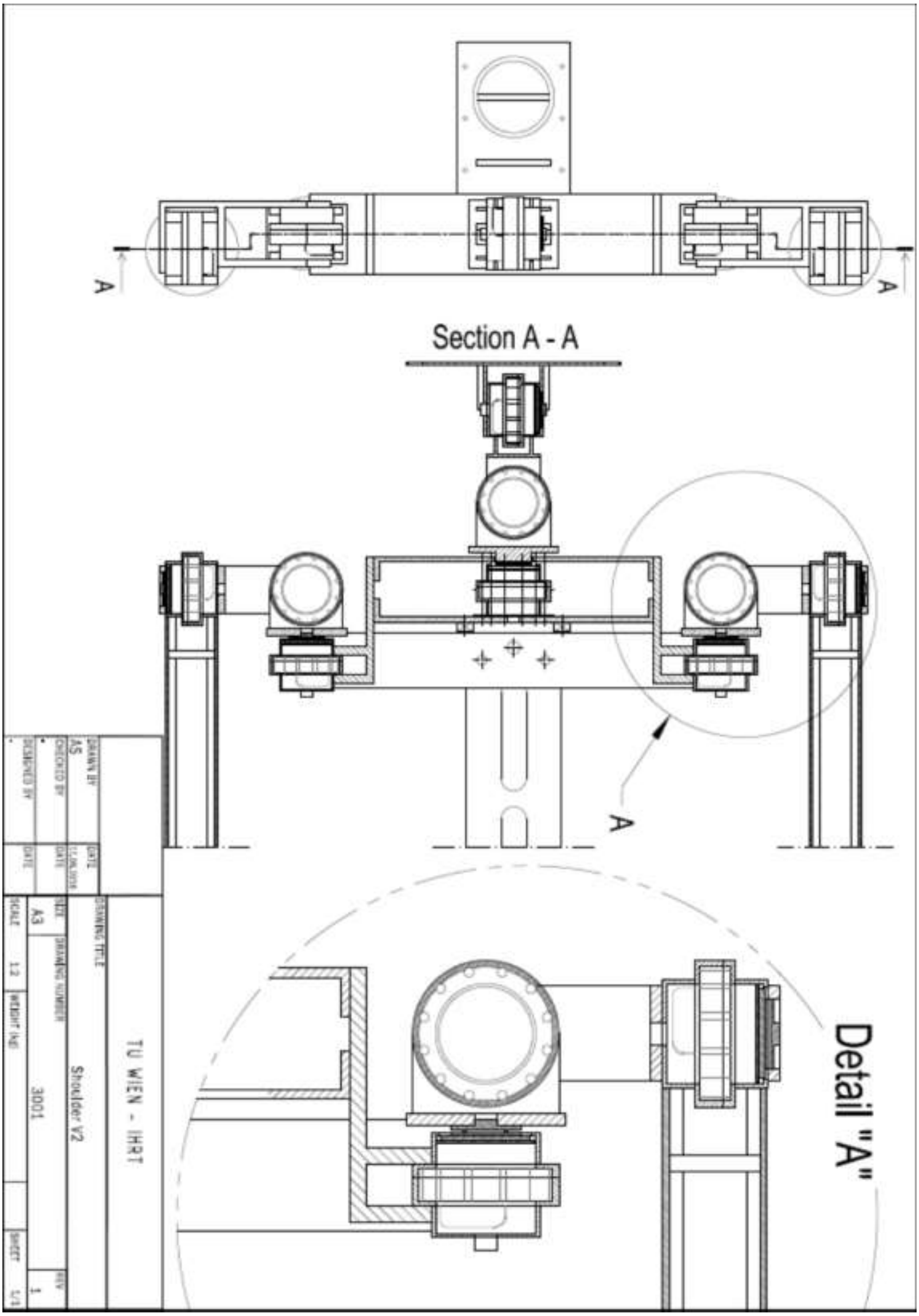
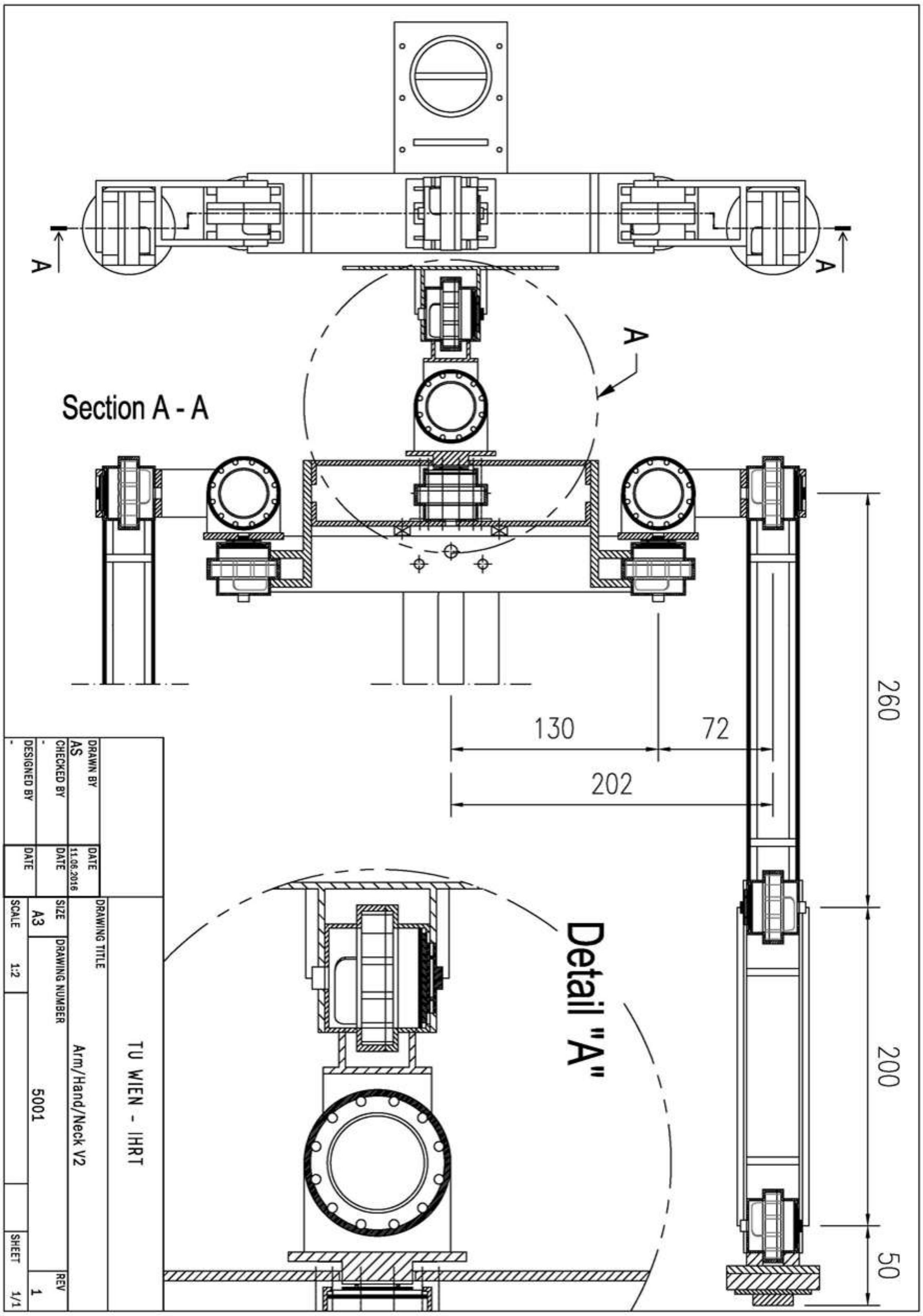


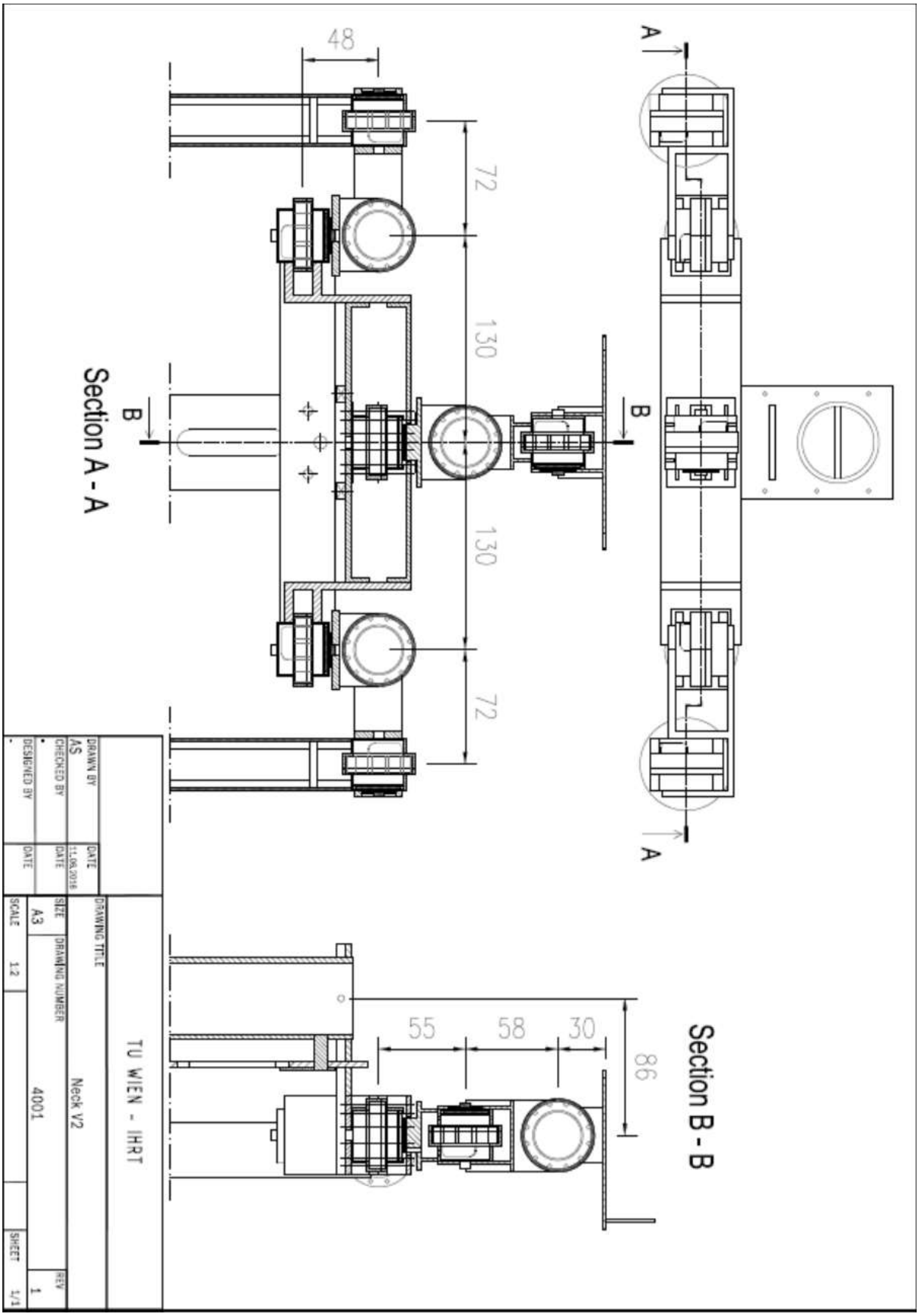
Figure 16-1. The second prototype (V2)

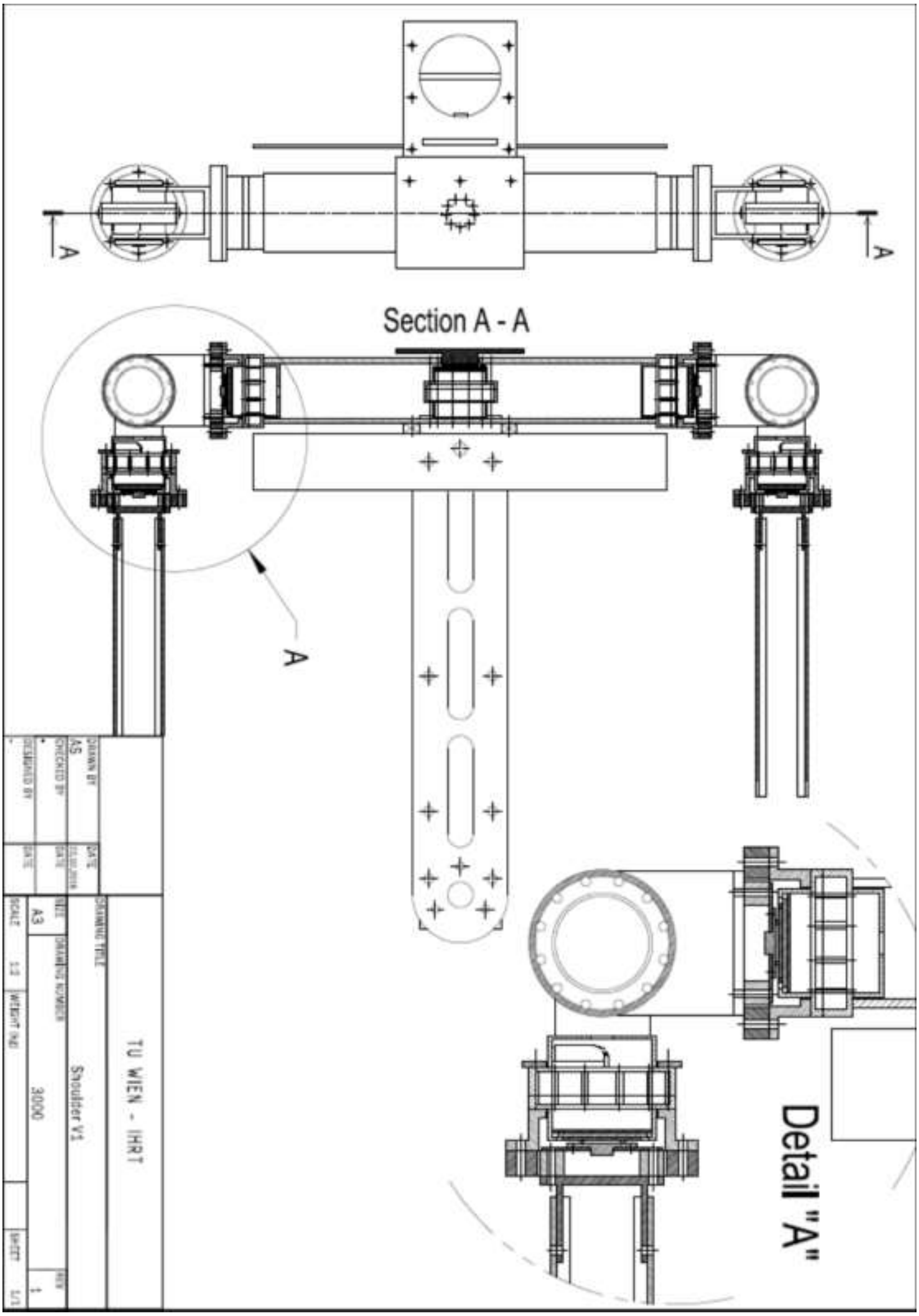

Front view
Left view
72
130
130
72
445
72
74
56
56
74
72
260
1052
1100
1155
1241
1260
840
720
640
415
155
80
34
86
54
28
35
55
260
200
TU WIEN - IHRT
DRAWN BY
AS
DATE
28.07.2018
CHECKED BY
–
DATE
DESIGNED BY
–
DATE
DRAWING TITLE
Version 1 – Dimensions
SIZE
A4
DRAWING NUMBER
1001
REV
1
SCALE
WEIGHT (kg)
SHEET
1/1


Section A - A
A
Detail "A"
TU WIEN - IHRT
Shoulder V2
3001
A3



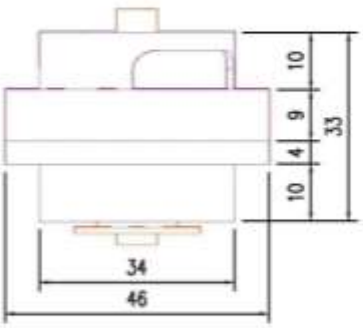
A
A
A
Section A - A
Detail "A"
130
72
202
260
200
50
DRAWN BY
AS
DATE
11.06.2016
CHECKED BY
-
DATE
DESIGNED BY
-
DATE
DRAWING TITLE
TU WIEN - IHRT
Arm/Hand/Neck V2
SIZE
A3
DRAWING NUMBER
5001
REV
1
SCALE
1:2
SHEET
1/1


Section A - A
Section B - B
A
B
48
72
130
130
72
55
58
30
86
TU WIEN - IHRT
DRAWING TITLE
Neck V2
DRAWN BY
AS
DATE
11.06.2018
CHECKED BY
DESIGNED BY
SIZE
A3
DRAWING NUMBER
4001
REV
1
SCALE
1:2
SHEET
1/1


Section A - A
A
Detail "A"
TU WIEN - IHRT
Shoulder V1
3000
A3
DRAWN BY
CHECKED BY
DESIGNED BY
DRAWING TITLE
DRAWING NUMBER
SCALE
WEIGHT
SHEET
REV

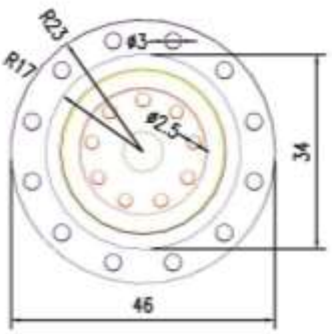
1

Top view



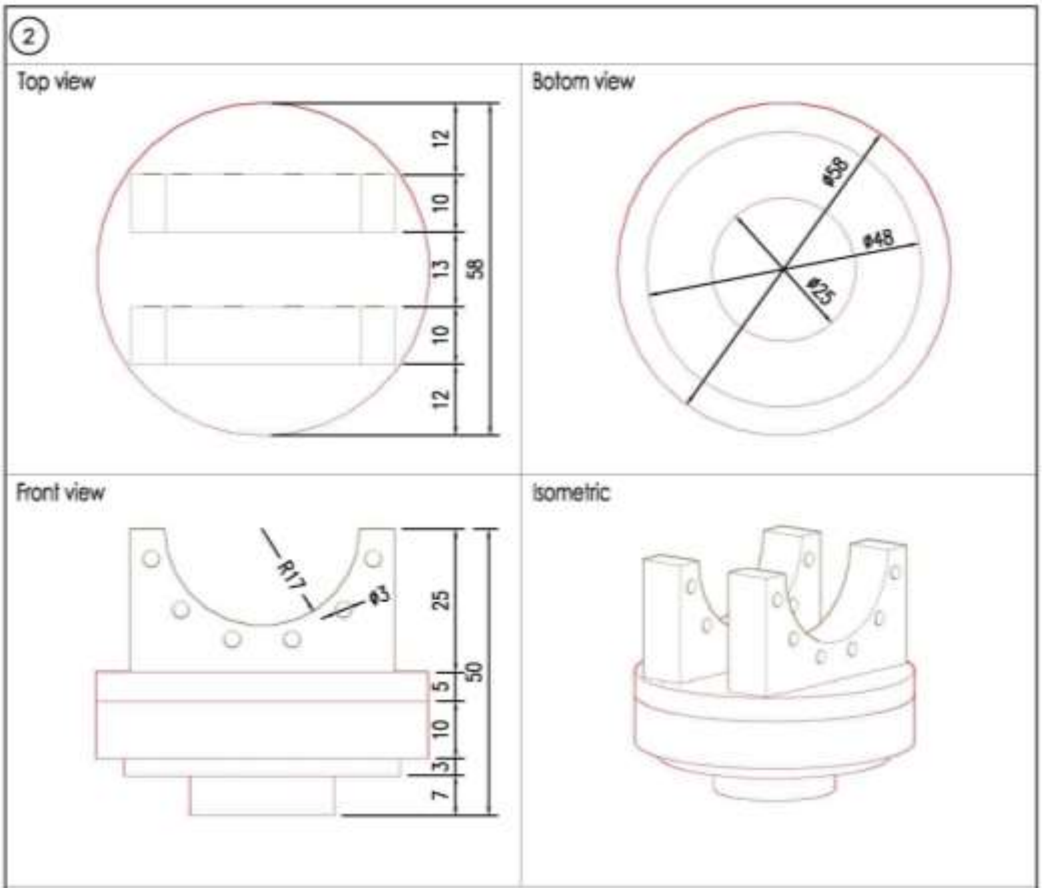
SW Isometric

Front view

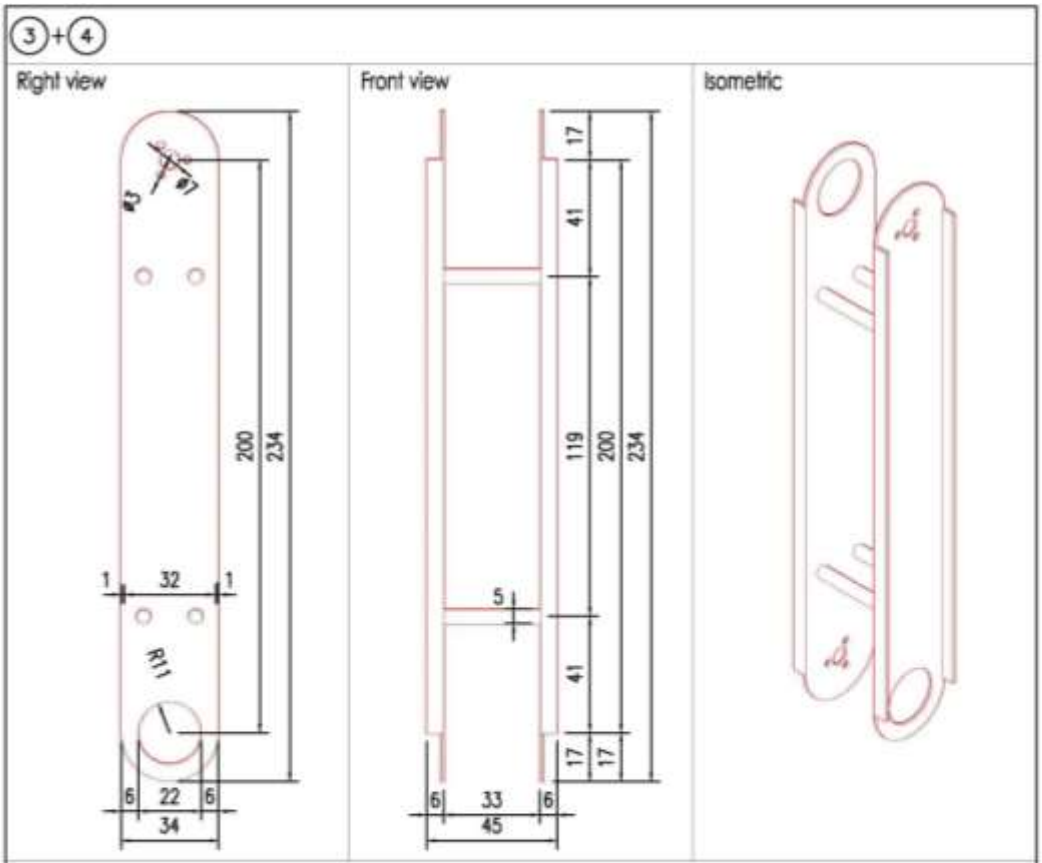


SE Isometric

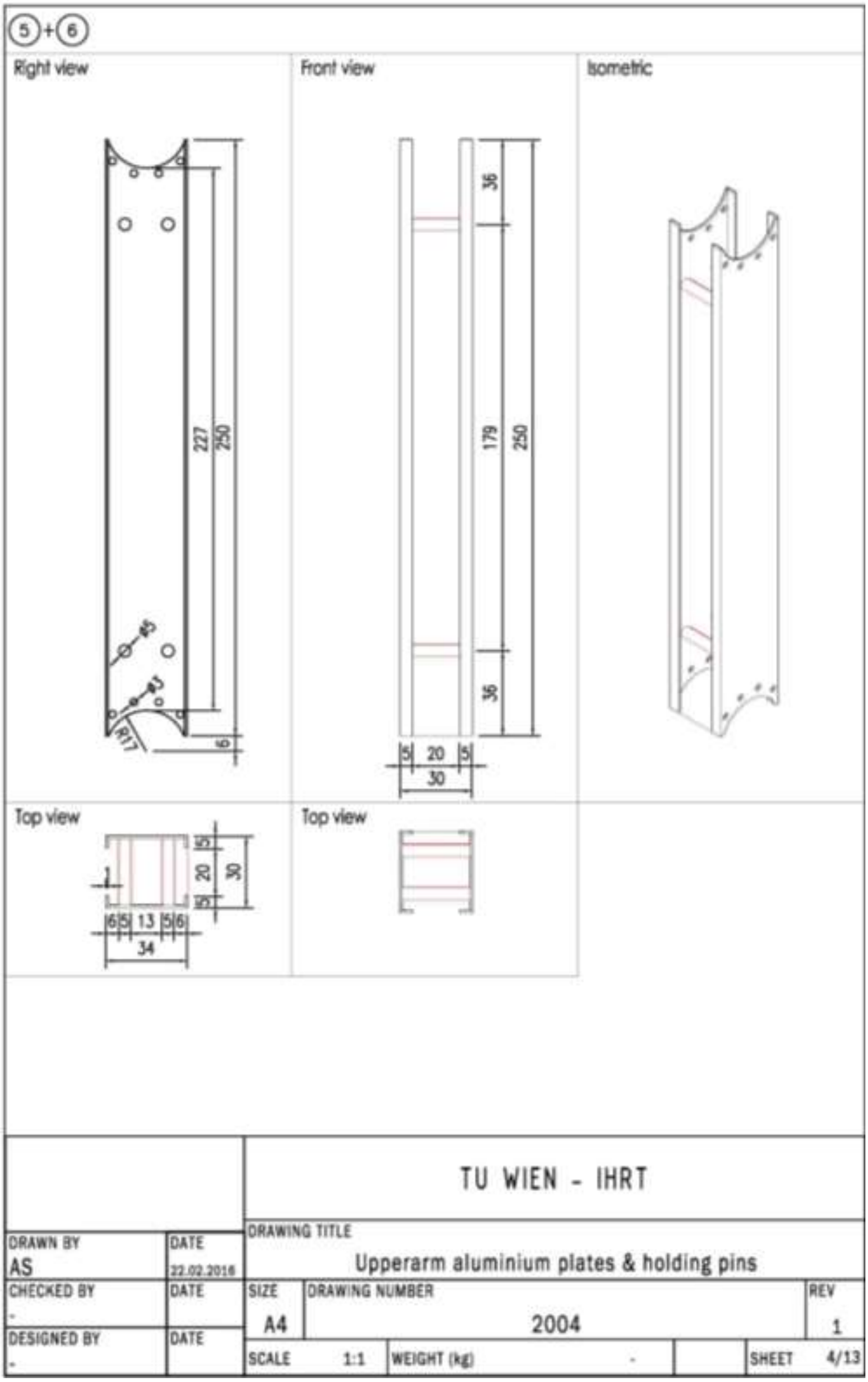
		TU WIEN - IHRT					
DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE DC Brushless motor					
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 2001				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	1/13



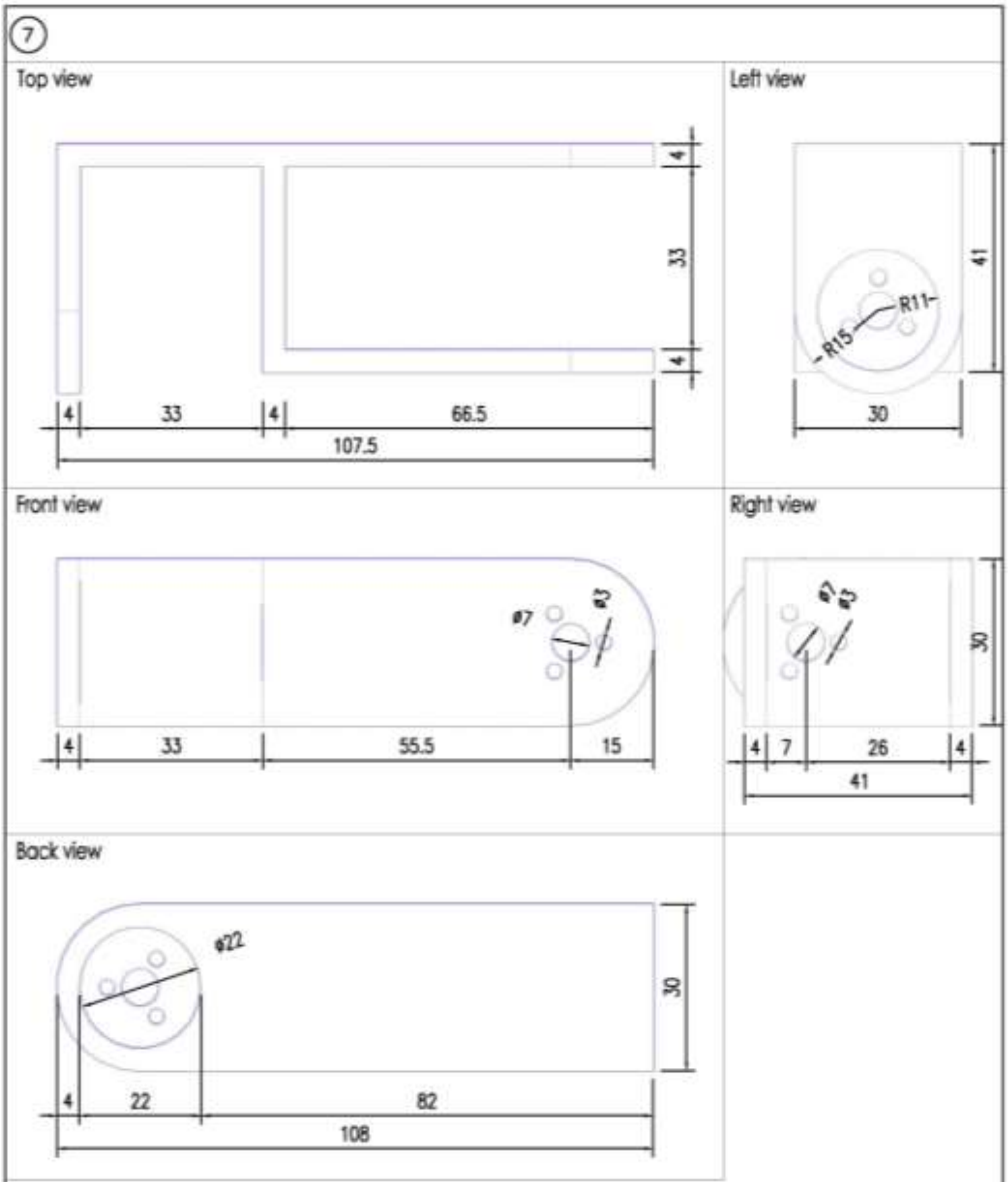
	TU WIEN - IHRT
DRAWN BY: AS	DATE: 22.02.2016
CHECKED BY: -	DATE:
DESIGNED BY: -	DATE:
DRAWING TITLE	Hand
SIZE	A4
DRAWING NUMBER	2002
REV	1
SCALE	1:1
WEIGHT (kg)	-
SHEET	2/13



		TU WIEN - IHRT			
DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Lower arm aluminium plates & holding pins			
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 3003		REV 1
DESIGNED BY -	DATE	SCALE 1:1	WEIGHT (kg) -		SHEET 3/13

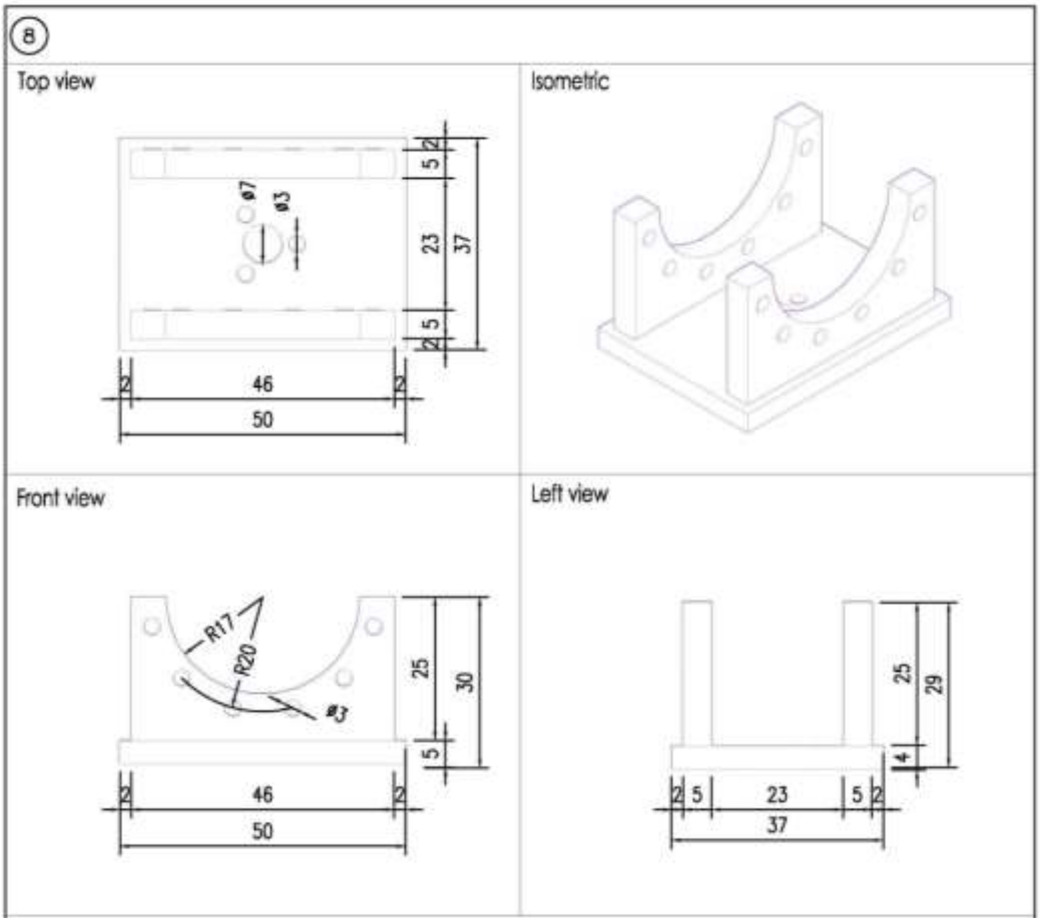


5 + 6
Right view
Front view
Isometric
227
250
36
179
250
36
Ø5
Ø3
R17
6
5 20 5
30
Top view
Top view
6 5 13 5 6
34
5 20 5
30
1
TU WIEN - IHRT
DRAWN BY
AS
DATE
22.02.2016
CHECKED BY
-
DATE
DESIGNED BY
-
DATE
DRAWING TITLE
Upperarm aluminium plates & holding pins
SIZE
A4
DRAWING NUMBER
2004
REV
1
SCALE 1:1
WEIGHT (kg) -
SHEET 4/13

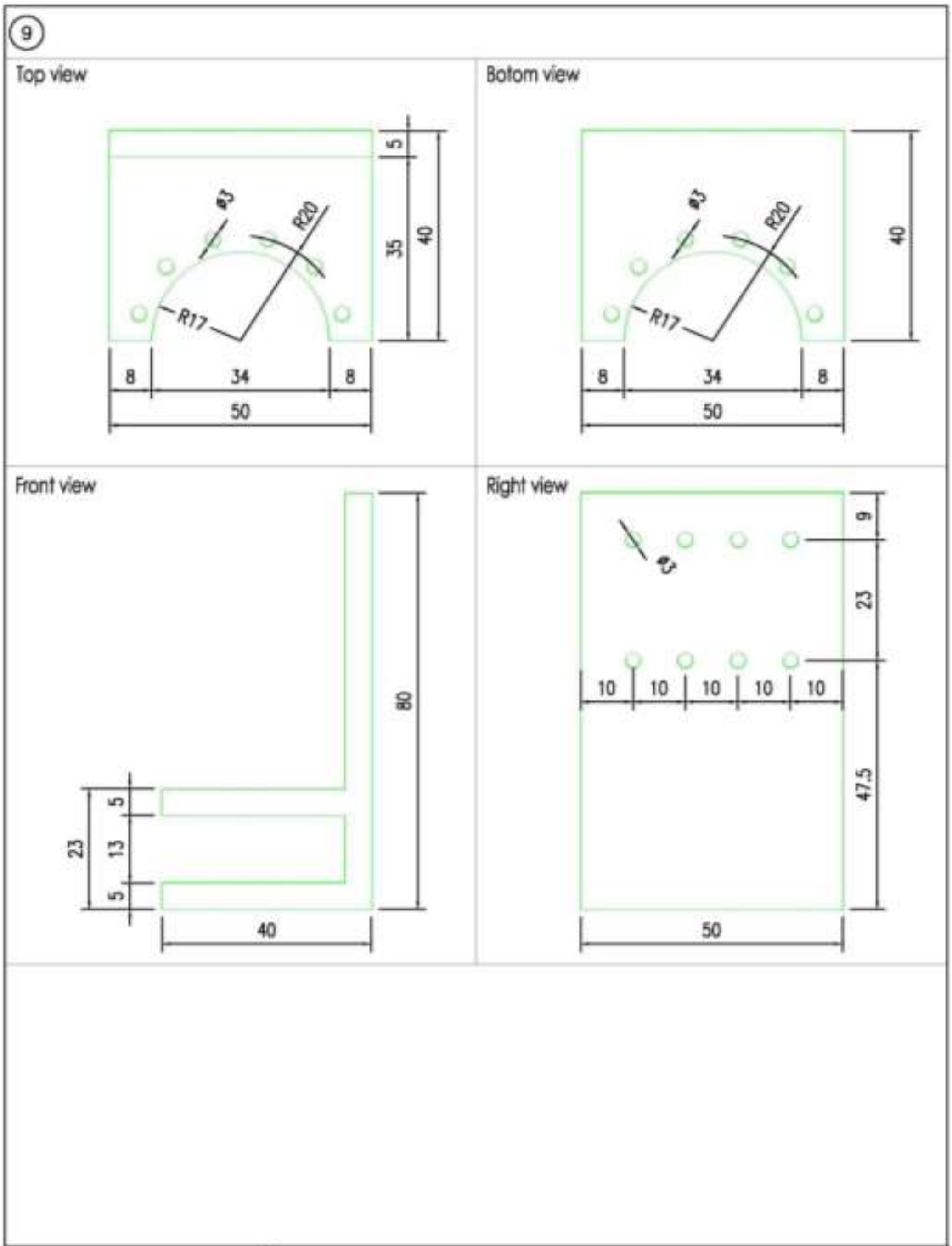


TU WIEN - IHRT

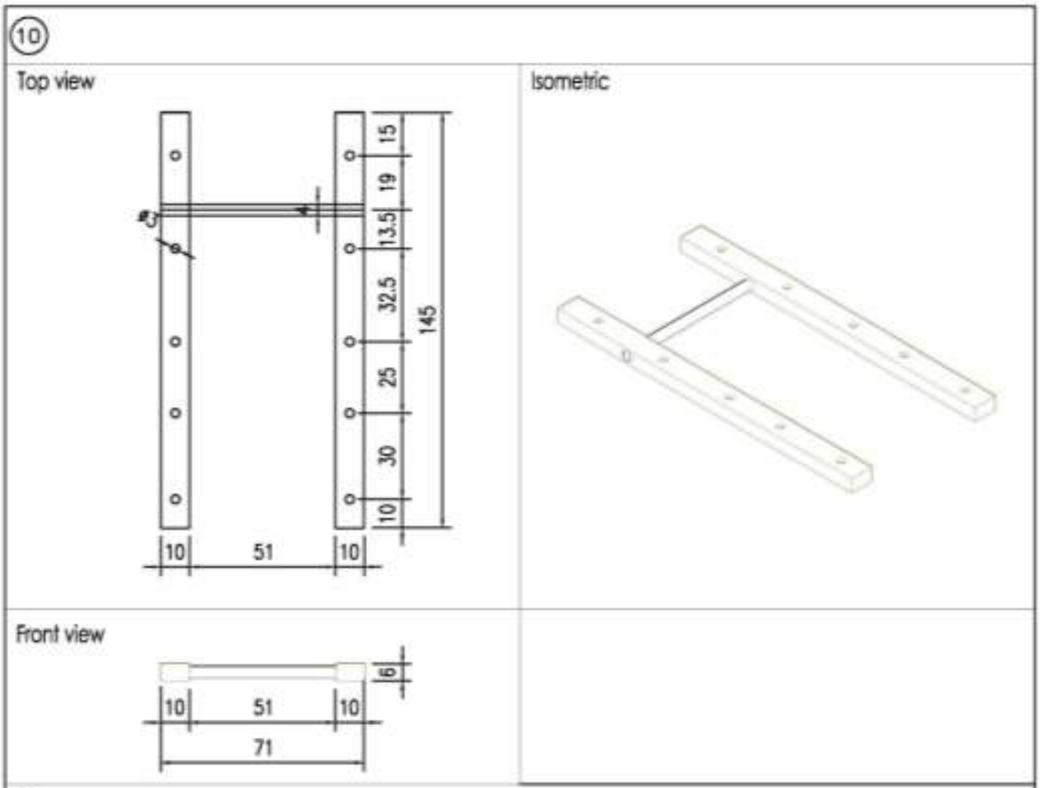
DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Shoulder/Arm joint connector					
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 2005				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	5/13

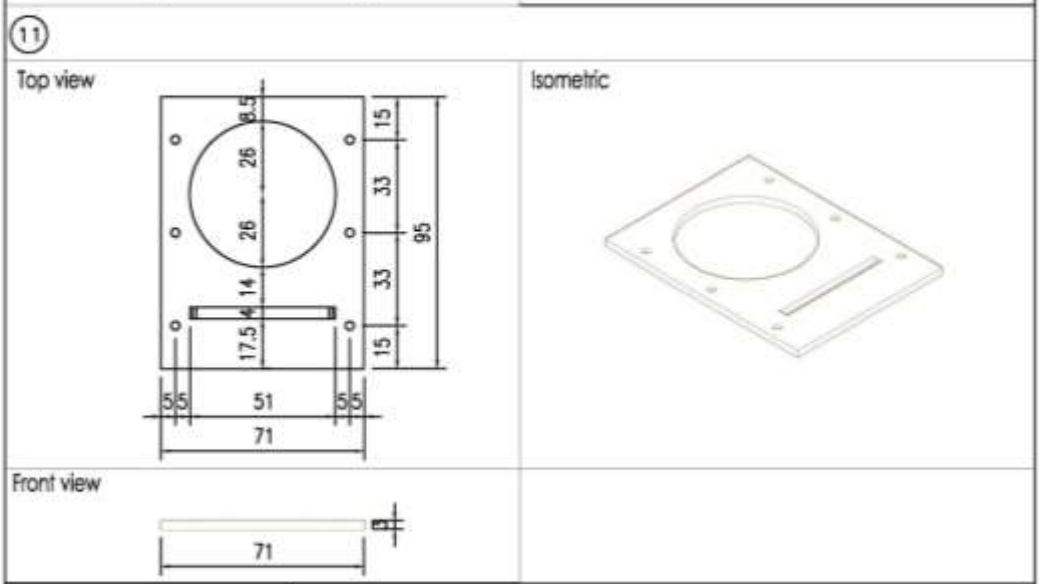


		TU WIEN - IHRT
DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Shoulder joint connector
CHECKED BY -	DATE	SIZE A4 · DRAWING NUMBER 2006 · REV 1
DESIGNED BY -	DATE	SCALE 1:1 · WEIGHT (kg) - · SHEET 6/13



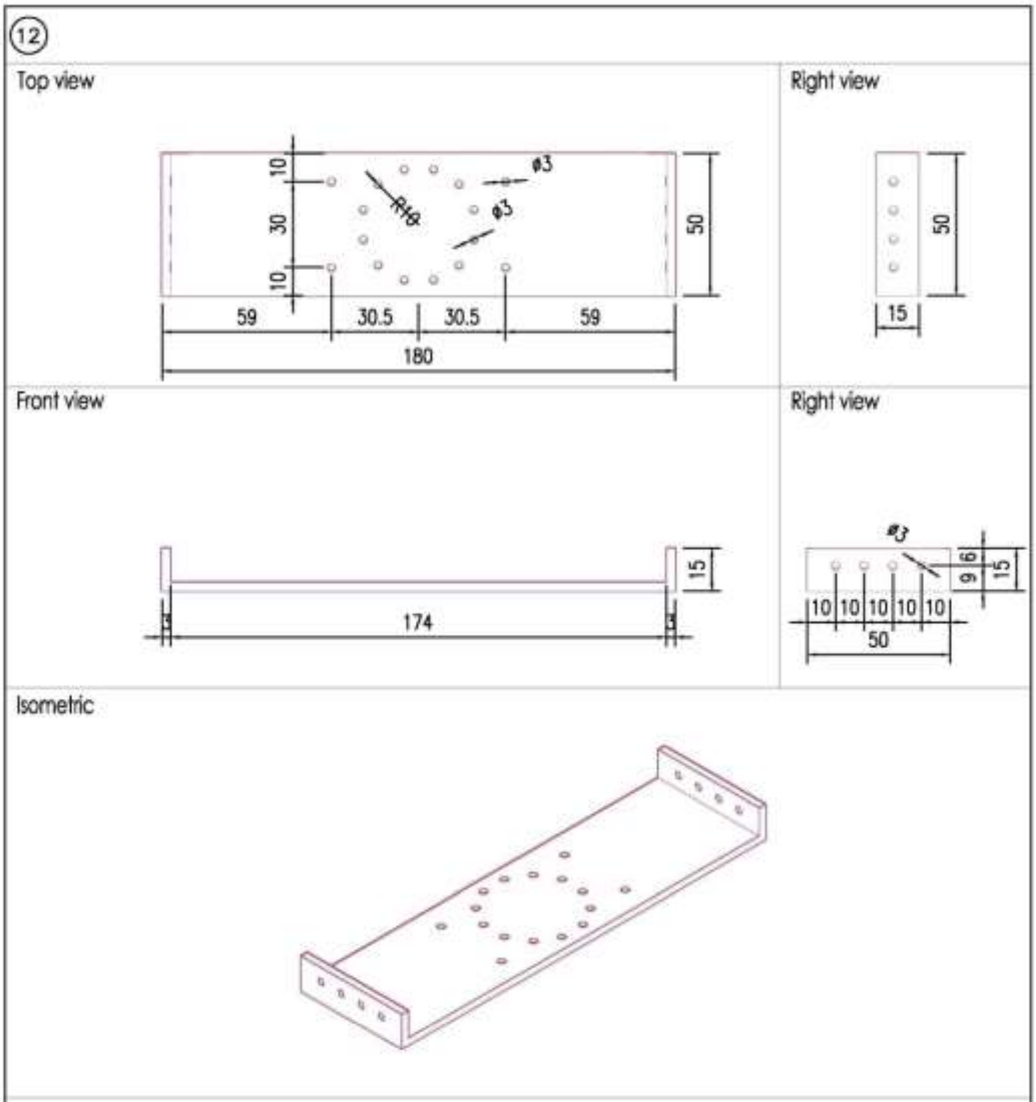
		TU WIEN - IHRT					
DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Shoulder/Neck joint connector					
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 2007				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	7/13





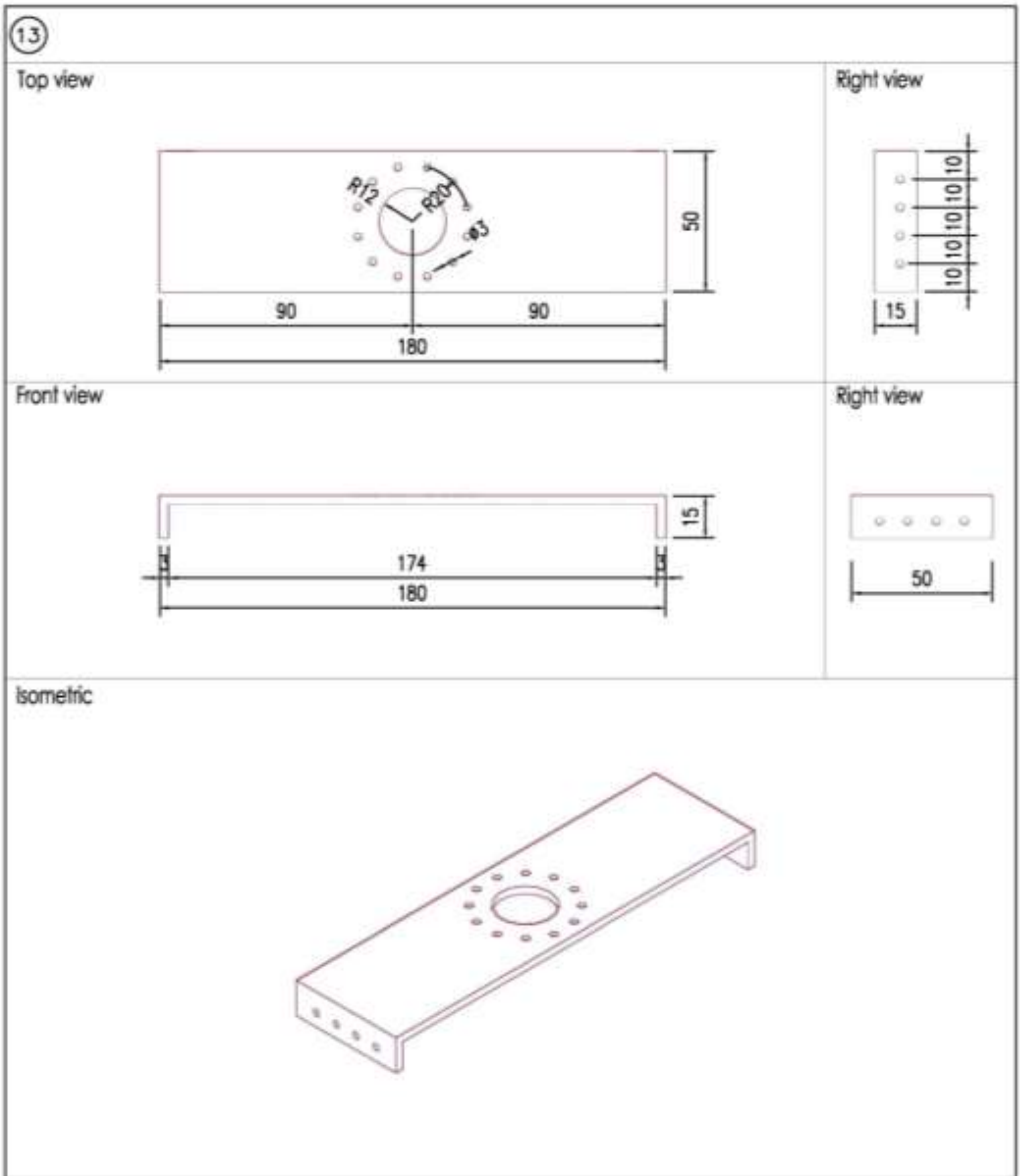
TU WIEN - IHRT

DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Neck holding plates & rods	
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 2008	REV 1
DESIGNED BY -	DATE	SCALE 1:1	WEIGHT (kg) -	SHEET 8/13



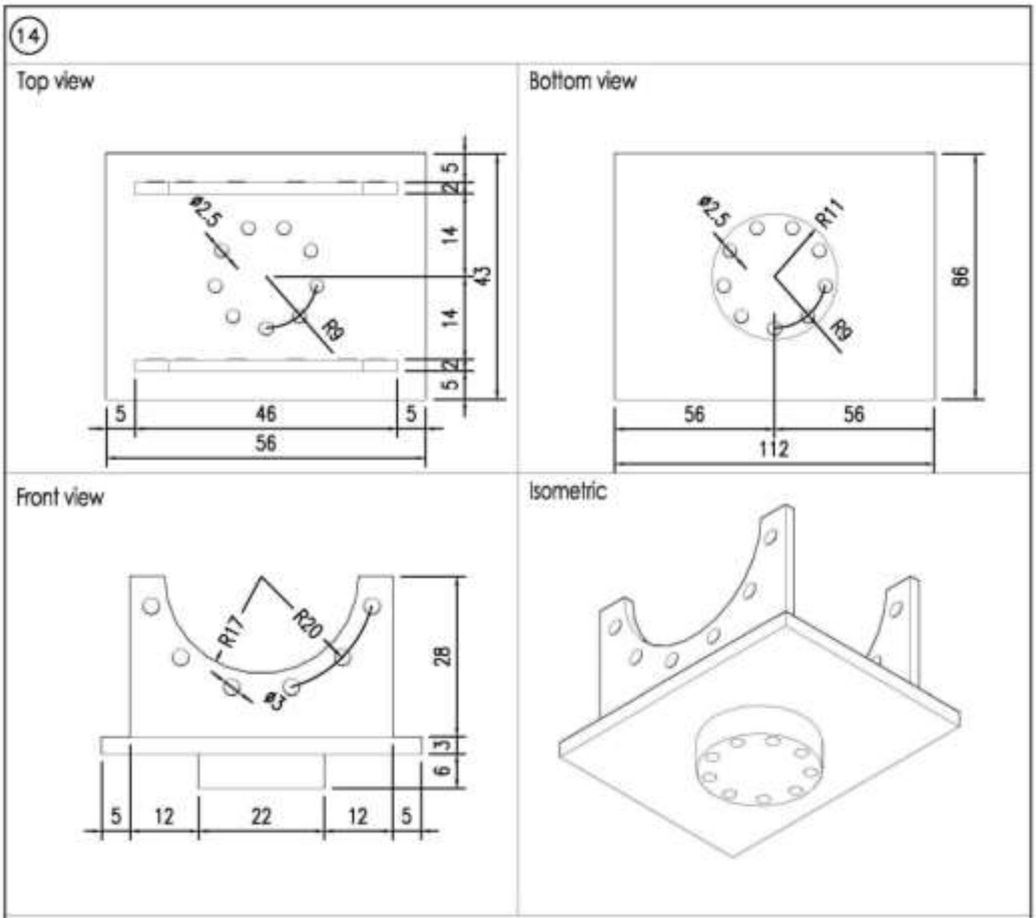
TU WIEN - IHRT

DRAWN BY: AS	DATE: 22.02.2016	DRAWING TITLE: Lower shoulder bracket				
CHECKED BY: -	DATE	SIZE: A4	DRAWING NUMBER: 2009			REV: 1
DESIGNED BY: -	DATE	SCALE: 1:1	WEIGHT (kg): -		SHEET	9/13

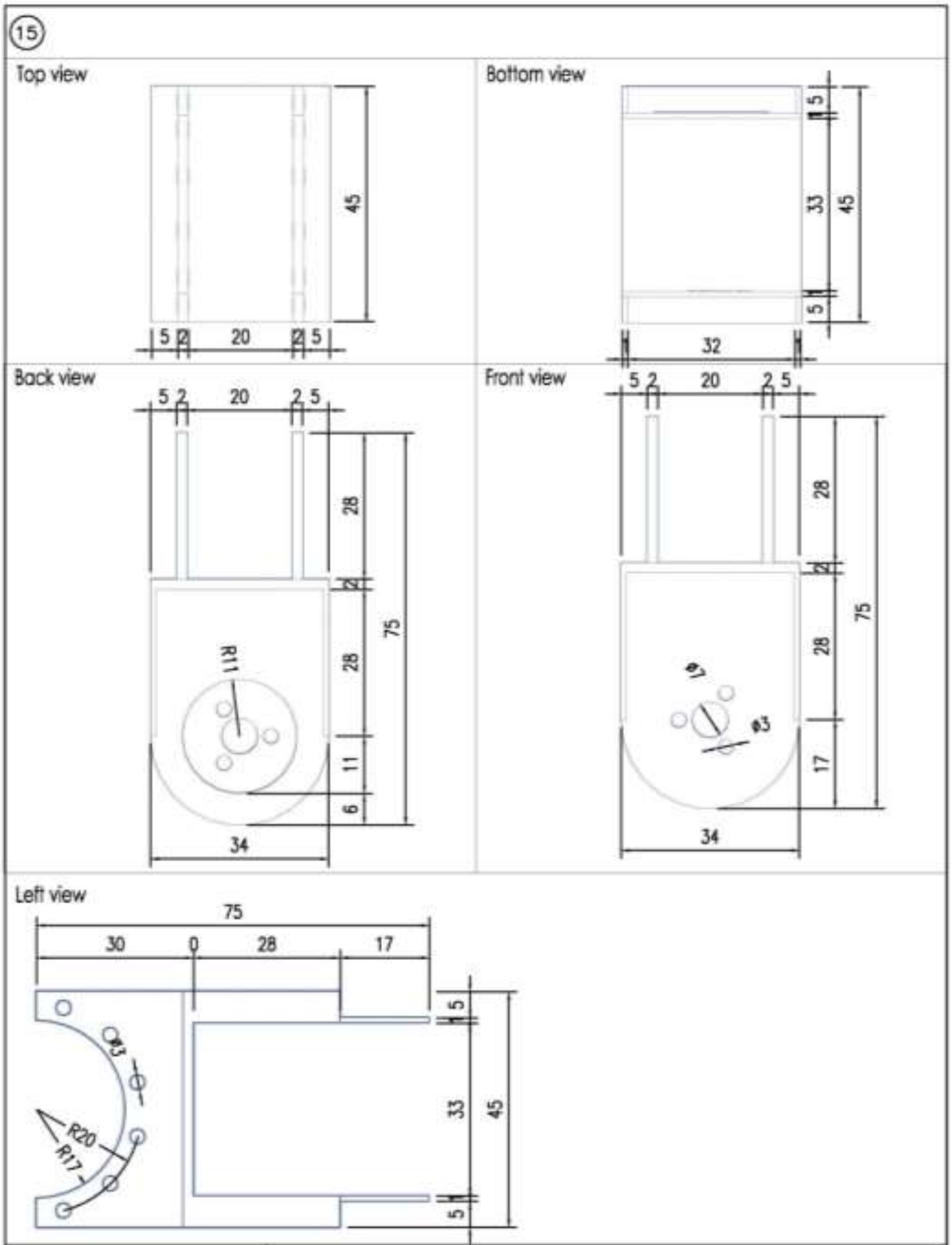


TU WIEN - IHRT

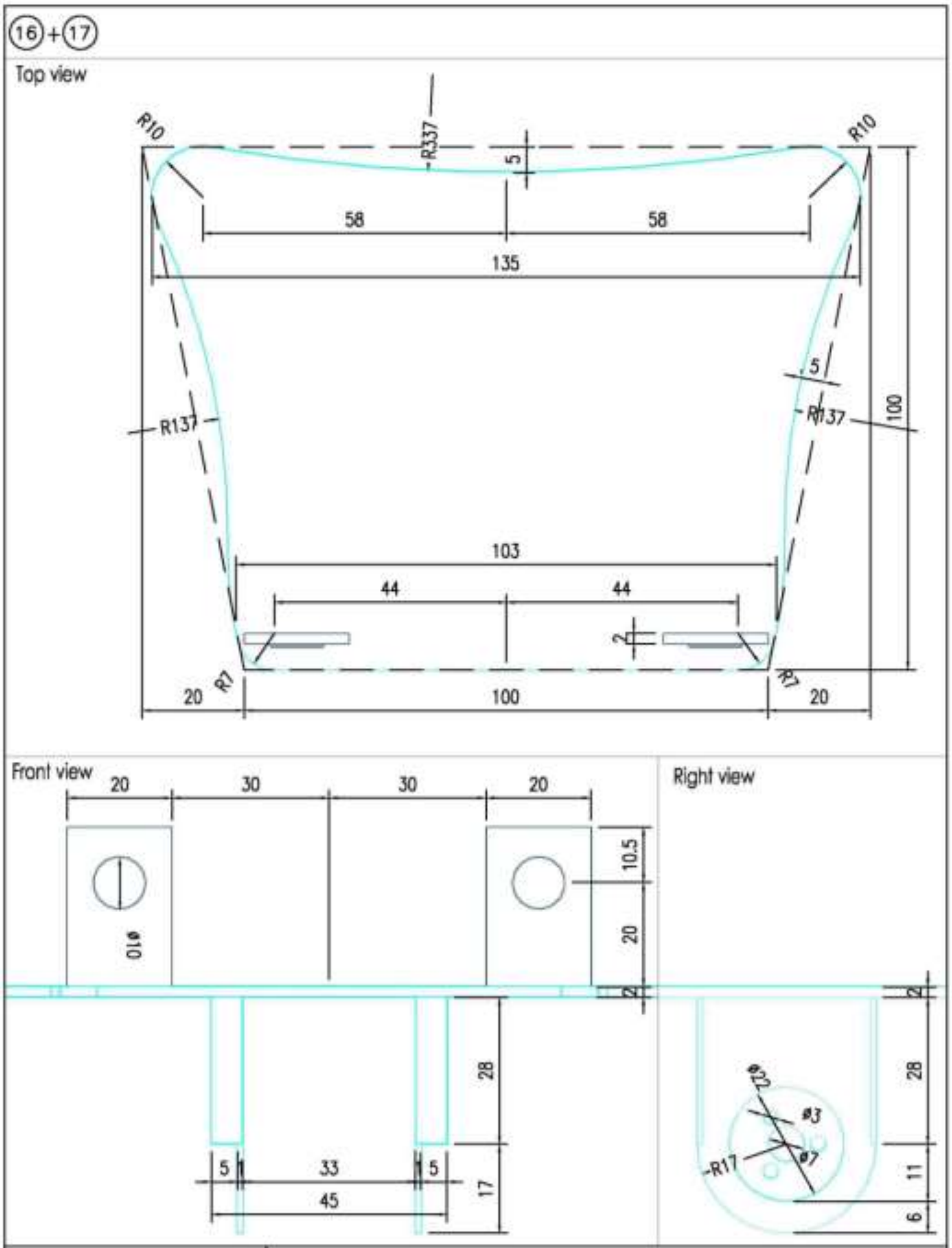
DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Upper shoulder bracket			
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 2010		REV 1
DESIGNED BY -	DATE	SCALE 1:1	WEIGHT (kg) -		SHEET 10/13



		TU WIEN - IHRT				
DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Holder of neck DC motor				
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 2011			REV 1
DESIGNED BY -	DATE	SCALE 1:1	WEIGHT (kg) -		SHEET	11/13



		TU WIEN - IHRT				
DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Holder of linear actuators				
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 2012			REV 1
DESIGNED BY -	DATE	SCALE 1:1	WEIGHT (kg) -		SHEET 12/13	



TU WIEN - IHRT

DRAWN BY AS	DATE 22.02.2016	DRAWING TITLE Platform for fixed cameras			
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 2013		REV 1
DESIGNED BY -	DATE	SCALE 1:1	WEIGHT (kg) -		SHEET 13/13

17 APPENDIX – C

Appendix C includes the parts that constitute the design of the neck/head of the third prototype (Version three V3). The numbers of the parts building the prototype have been presented. Distribution of the mass and each part according to the respective number has been described with dimensions and their view has been presented also.

17.1 Mass properties of upper body V3

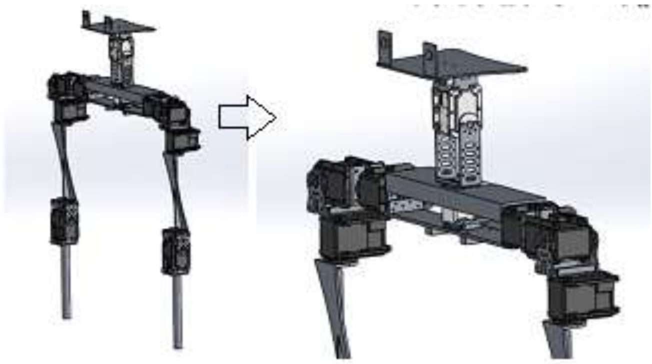


Figure 17-1. The third prototype (V3)

Mass = 1815.18 g, Volume = 914465.16 mm^3, surface area = 377205.23 mm^2, centre of mass: (X = 294.44, Y = 145.73, Z = 359.99) mm;

Principal axes of inertia and principal moments of inertia: ($g * mm^2$): Taken at the centre of mass.

Ix = (1.00, 0.00, 0.00)	Px = 31708612.87
Iy = (0.00, -0.03, -1.00)	Py = 46799542.88
Iz = (0.00, 1.00, -0.03)	Pz = 76837021.85

Moments of inertia ($g * mm^2$): Taken at the centre of mass and aligned with the output coordinate system.

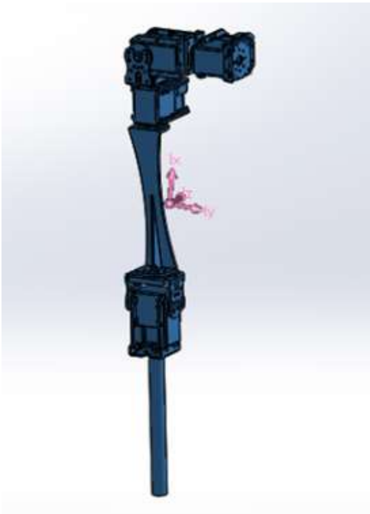
Lxx = 31708612.91	Lxy = -5.48	Lxz = 819.02
Lyx = -5.48	Lyy = 76801355.82	Lyz = 1034430.01
Lzx = 819.02	Lzy = 1034430.01	Lzz = 46835208.86

Taken at the output coordinate system;

Ixx = 305497822.46	Ixy = 77887356.19	Ixz = 192406559.54
Iyx = 77887356.19	Iyy = 469412580.21	Iyz = 96261634.54

Izx = 192406559.54   Izy = 96261634.54   Izz = 242754670.99

17.2 Arm V3



Mass properties of Arm V3; mass = 812.82 g, volume = 349314.49 mm^3, surface area = 121950.70 mm^2, centre of mass:(X = -167.39, Y = -11.17, Z = -57.44) mm;
Principal axes of inertia and principal moments of inertia ($g * mm^2$): Taken at the centre of mass.

Ix = (0.10, 0.03, 0.99)   Px = 714423.77
Iy = (0.99, 0.11, -0.11   Py = 20422491.68
Iz = (-0.11, 0.99, -0.02   Pz = 20850427.03

Moments of inertia ($g * mm^2$);

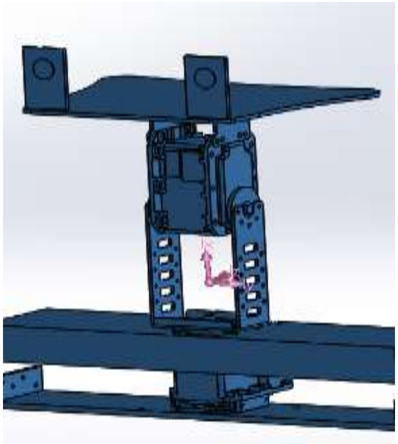
- Taken at the centre of mass and aligned with the output coordinate system.

Lxx = 20211972.69	Lxy = 113314.22	Lxz = 2047587.90
Lyx = 113314.22	Lyy = 20824209.77	Lyz = 648731.30
Lzx = 2047587.90	Lzy = 648731.30	Lzz = 951160.02

- Taken at the output coordinate system.

Ixx = 22994805.81	Ixy = 1633428.00	Ixz = 9862154.03
Iyx = 1633428.00	Iyy = 46280281.93	Iyz = 1170320.15
Izx = 9862154.03	Izy = 1170320.15	Izz = 23827321.26

17.3 Head/Neck V3



Mass properties of Neck/Head V3; mass = 411.23 *g* (4.1123 *kg)*, volume = 183648.33mm^3, surface area = 111781.61mm^2, centre of mass: (X = -180.30, Y = -27.67, Z = 29.45) mm. During simulation I have increase a mass of arms about 200 *g* Principal axes of inertia and principal moments of inertia ($g * mm^2$): Taken at the centre of mass.

Ix = (0.00, -0.12, 0.99)	Px = 979747.22
Iy = (1.00, 0.00, 0.00)	Py = 1512214.57
Iz = (0.00, 0.99, 0.12)	Pz = 2255141.97

Moments of inertia ($g * mm^2$):

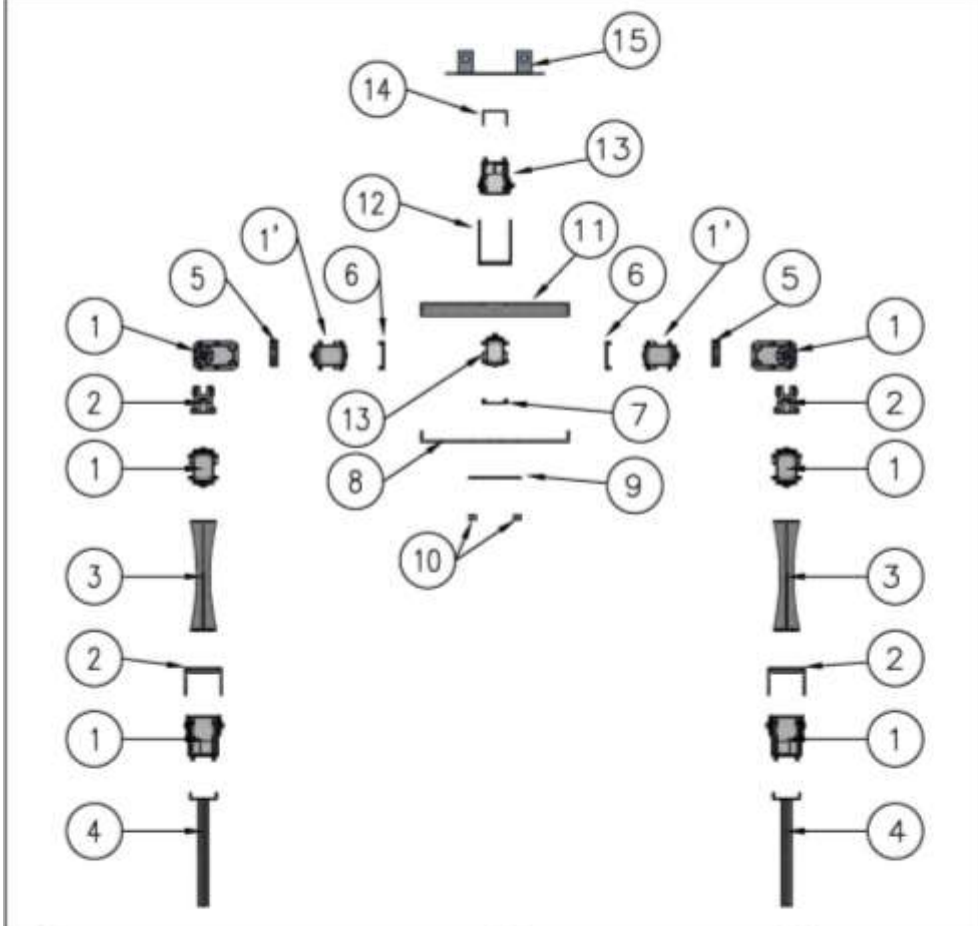
- Taken at the centre of mass and aligned with the output coordinate system.

Lxx = 1512214.21	Lxy = -3.71	Lxz = 443.19
Lyx = -3.71	Lyy = 2237854.19	Lyz = -147478.35
Lzx = 443.19	Lzy = -147478.35	Lzz = 997035.36

- Taken at the output coordinate system.

Ixx = 2183765.78	Ixy = 2051509.91	Ixz = -2183430.99
Iyx = 2051509.91	Iyy = 15963658.15	Iyz = -482598.92
Izx = -2183430.99	Izy = -482598.92	Izz = 14680906.81

Neck & Shoulder parts position

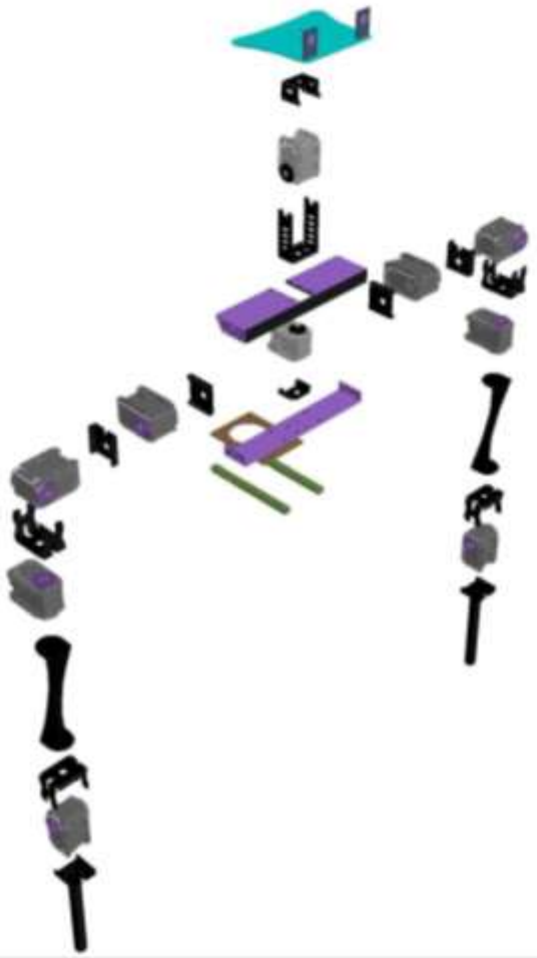


1. RX-64 Dynamixel Robot Servo Actuator
2. FR05-H1(OF-64H)
3. Arm
4. Forearm
5. FR05-S1(OF-64S)
6. FR05-B1(OF-64B)
7. FR07-B101 (RX-28)
8. Shoulder plate down
9. Spine holding plate
10. Spine holding pins
11. Shoulder plate up
12. Modified FR07-H101 (RX-28)
13. RX-28 Dynamixel Robot Servo Actuator
14. Modified FR07-S101 (RX-28)
15. Camera plate

TU WIEN - IHRT

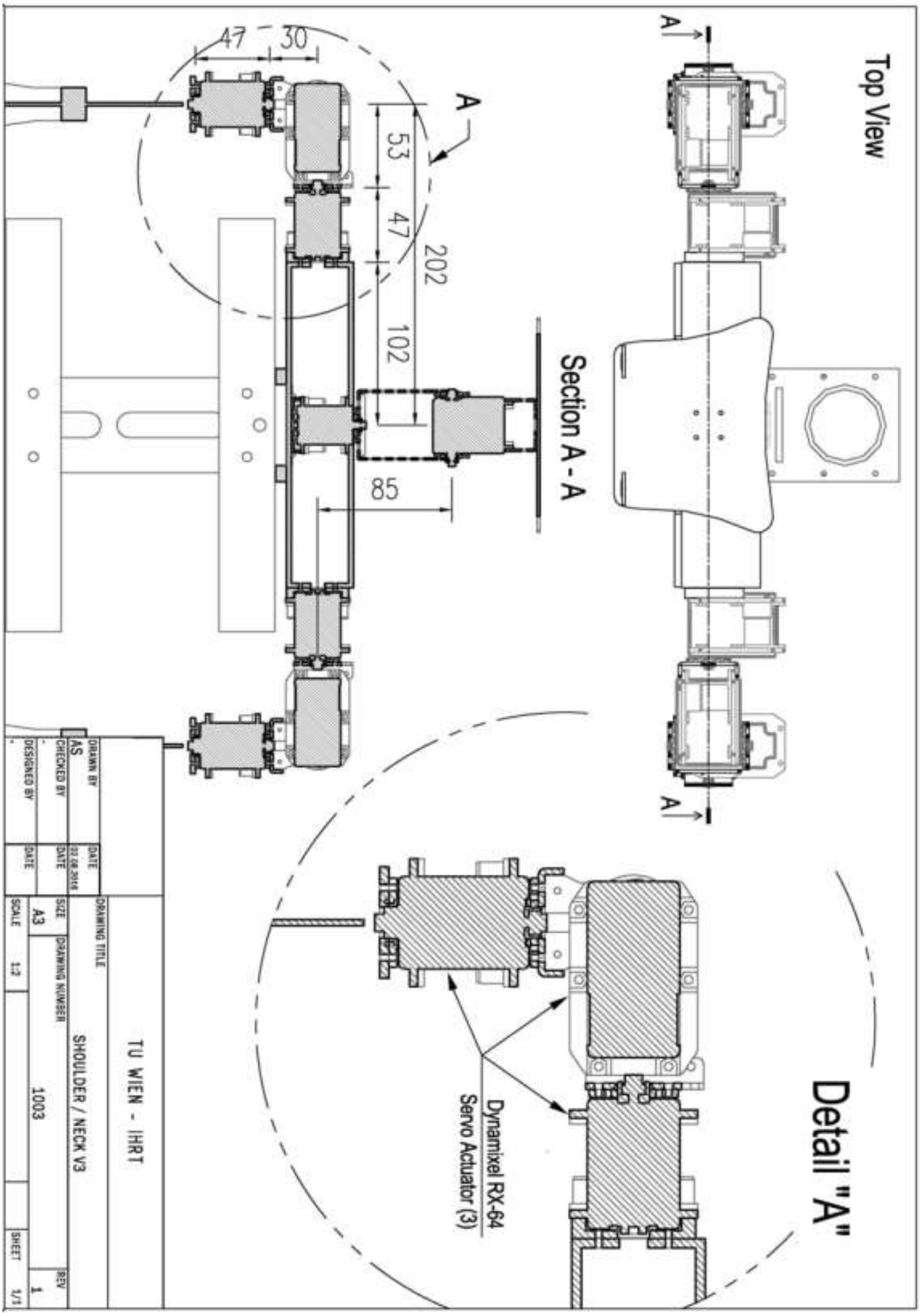
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE Neck & Shoulder parts position					
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 1001				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	1/16

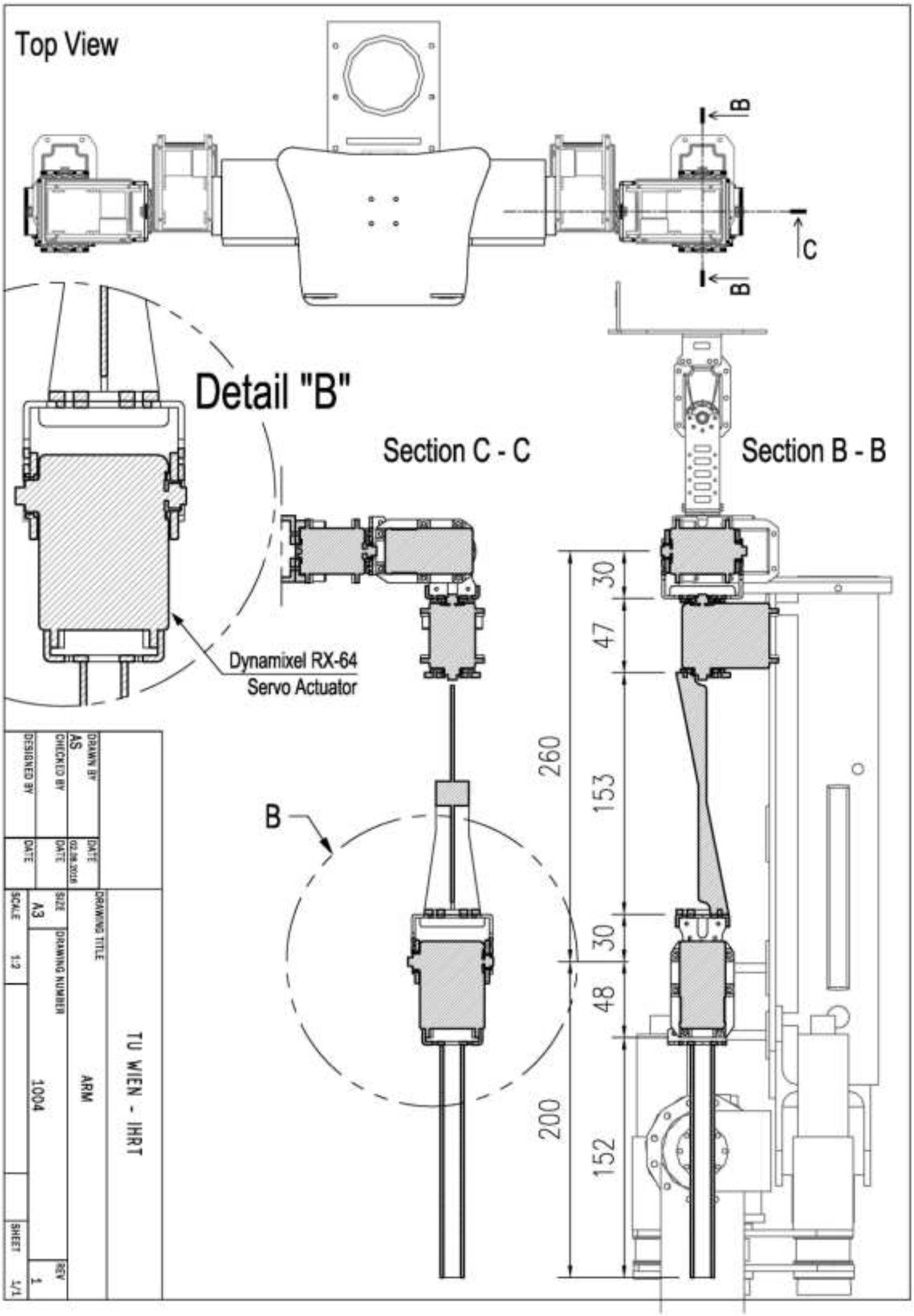
Neck & Shoulder parts position



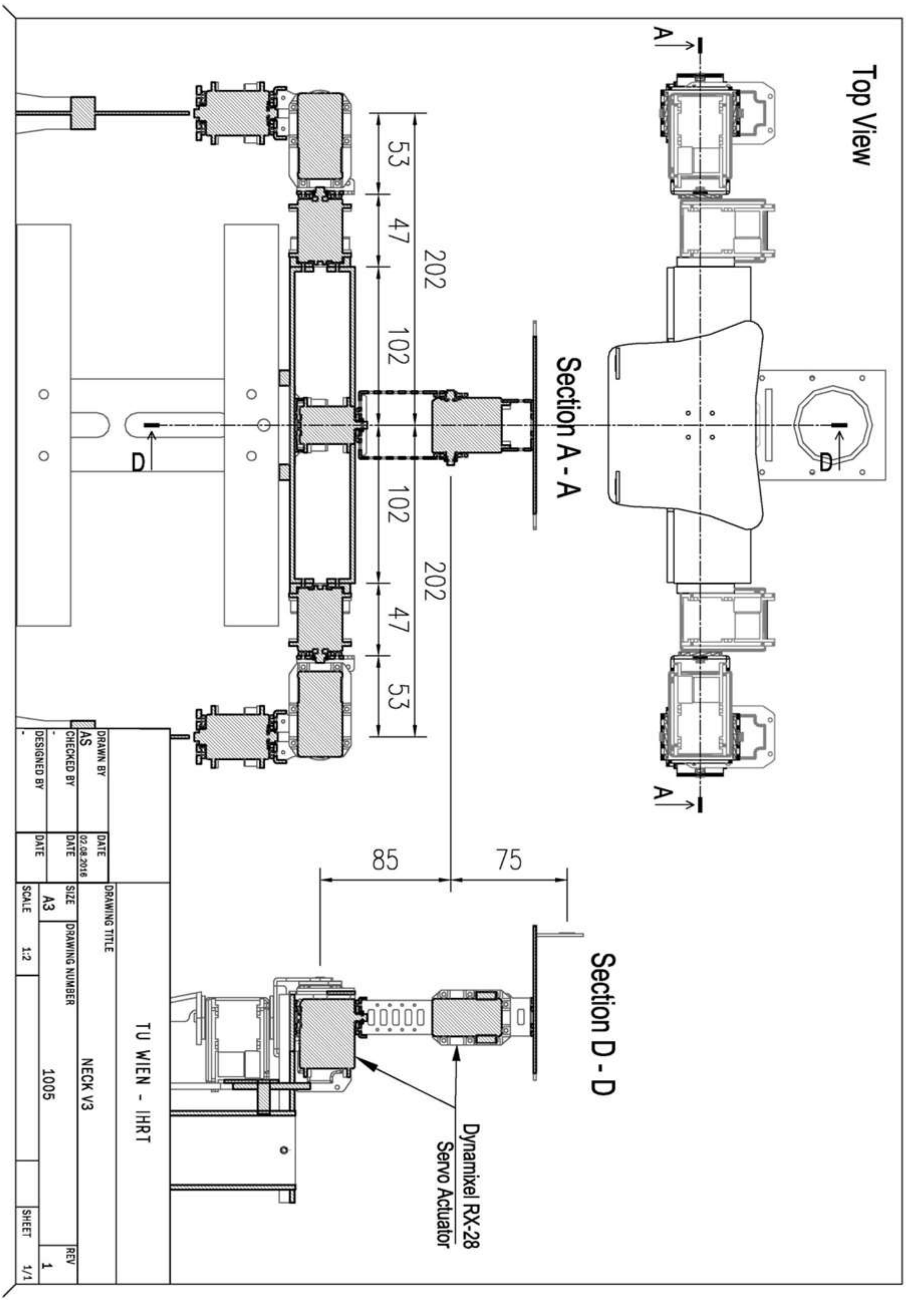
(1) RX-64 Dynamixel Robot Servo Actuator	(8) Shoulder plate down	(15) Camera plate
(2) FR05-H1(OF-64H)	(9) Spine holding plate	
(3) Arm	(10) Spine holding pins	
(4) Forearm	(11) Shoulder plate up	
(5) FR05-S1(OF-64S)	(12) Modified FR07-H101 (RX-28)	
(6) FR05-B1(OF-64B)	(13) RX-28 Dynamixel Robot Servo Actuator	
(7) FR07-B101 (RX-28)	(14) Modified FR07-S101 (RX-28)	

		TU WIEN - IHRT				
DRAWN BY: AS	DATE: 28.07.2016	DRAWING TITLE: Neck & Shoulder parts position - Exploded 3D view				
CHECKED BY: -	DATE	SIZE: A4	DRAWING NUMBER: 1002			REV: 1
DESIGNED BY: -	DATE	SCALE: 1:1	WEIGHT (kg): -		SHEET	2/16

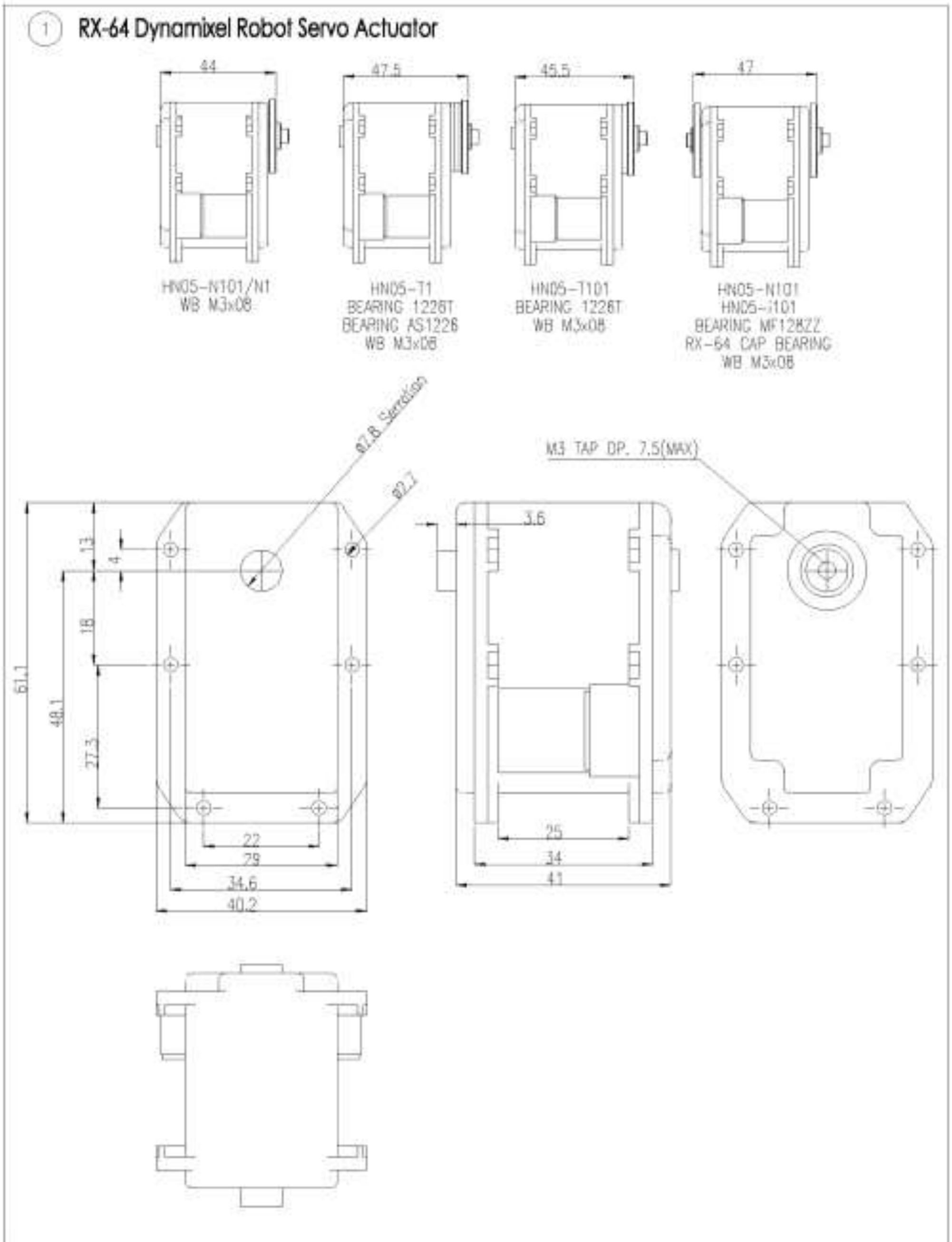

Top View
A
Section A - A
Detail "A"
Dynamixel RX-64
Servo Actuator (3)
47
30
53
47
202
102
85
DRAWN BY
AS
DATE
CHECKED BY
DESIGNED BY
DRAWING TITLE
SIZE
A3
DRAWING NUMBER
SCALE
1:2
SHEET
1/1
REV
1
TU WIEN - IHRT
SHOULDER / NECK V3
1003



Top View
B
C
B
Detail "B"
Section C - C
Section B - B
Dynamixel RX-64
Servo Actuator
B
30
47
260
153
30
48
200
152
DRAWN BY
AS
CHECKED BY
DESIGNED BY
DATE
02.08.2016
DATE
DATE
DRAWING TITLE
ARM
SIZE
A3
DRAWING NUMBER
1004
SCALE
1:2
REV
1
SHEET
1/1
TU WIEN - IHRT

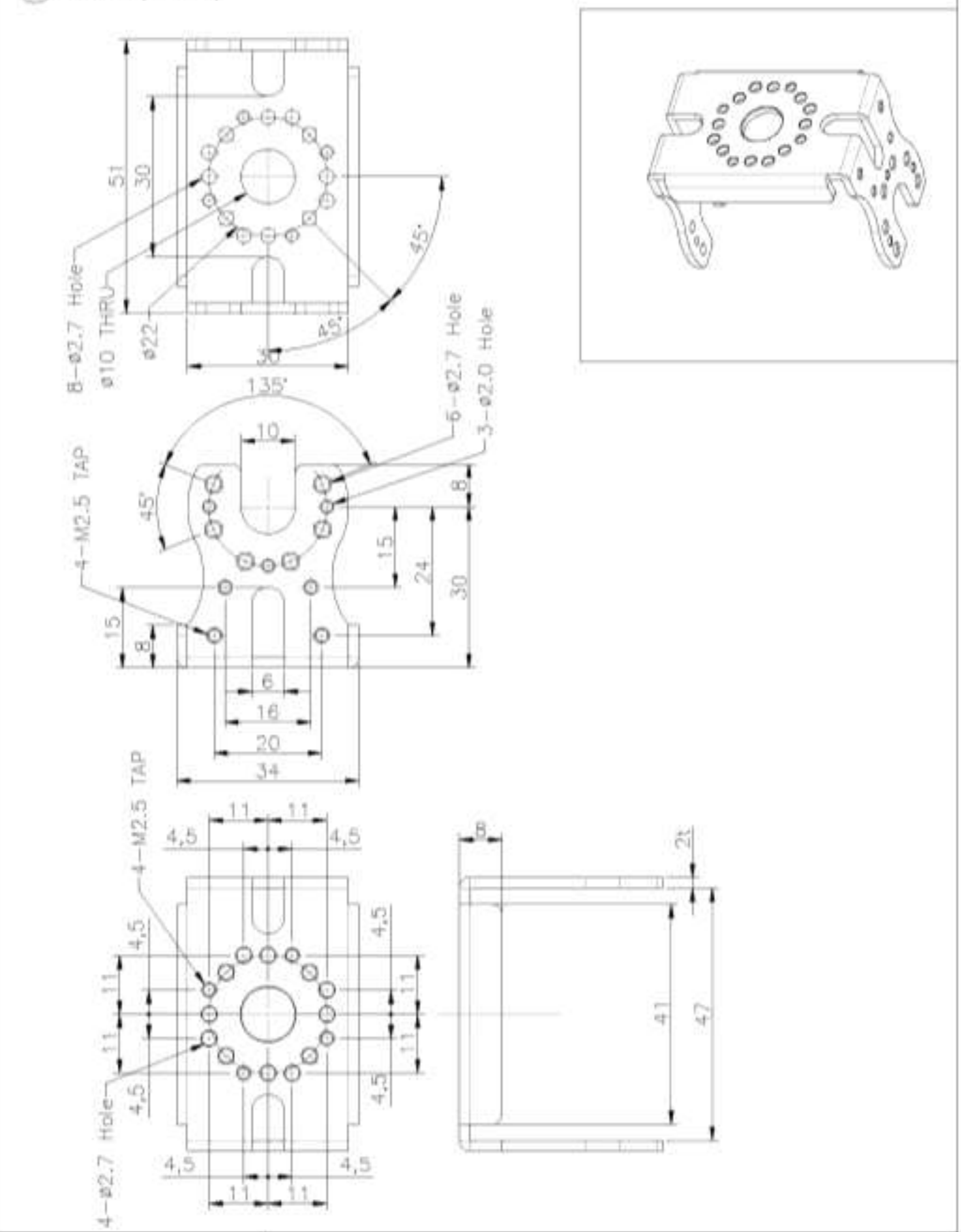

Top View
Section A - A
Section D - D
A
A
D
D
53
47
102
102
47
53
202
202
85
75
Dynamixel RX-28
Servo Actuator
TU WIEN - IHRT
DRAWING TITLE
NECK V3
DRAWN BY
AS
DATE
02.08.2016
CHECKED BY
-
DATE
DESIGNED BY
-
DATE
SIZE
A3
DRAWING NUMBER
1005
REV
1
SCALE
1:2
SHEET
1/1

17.4 Motor Dynamixel RX-64 for arm of Archie



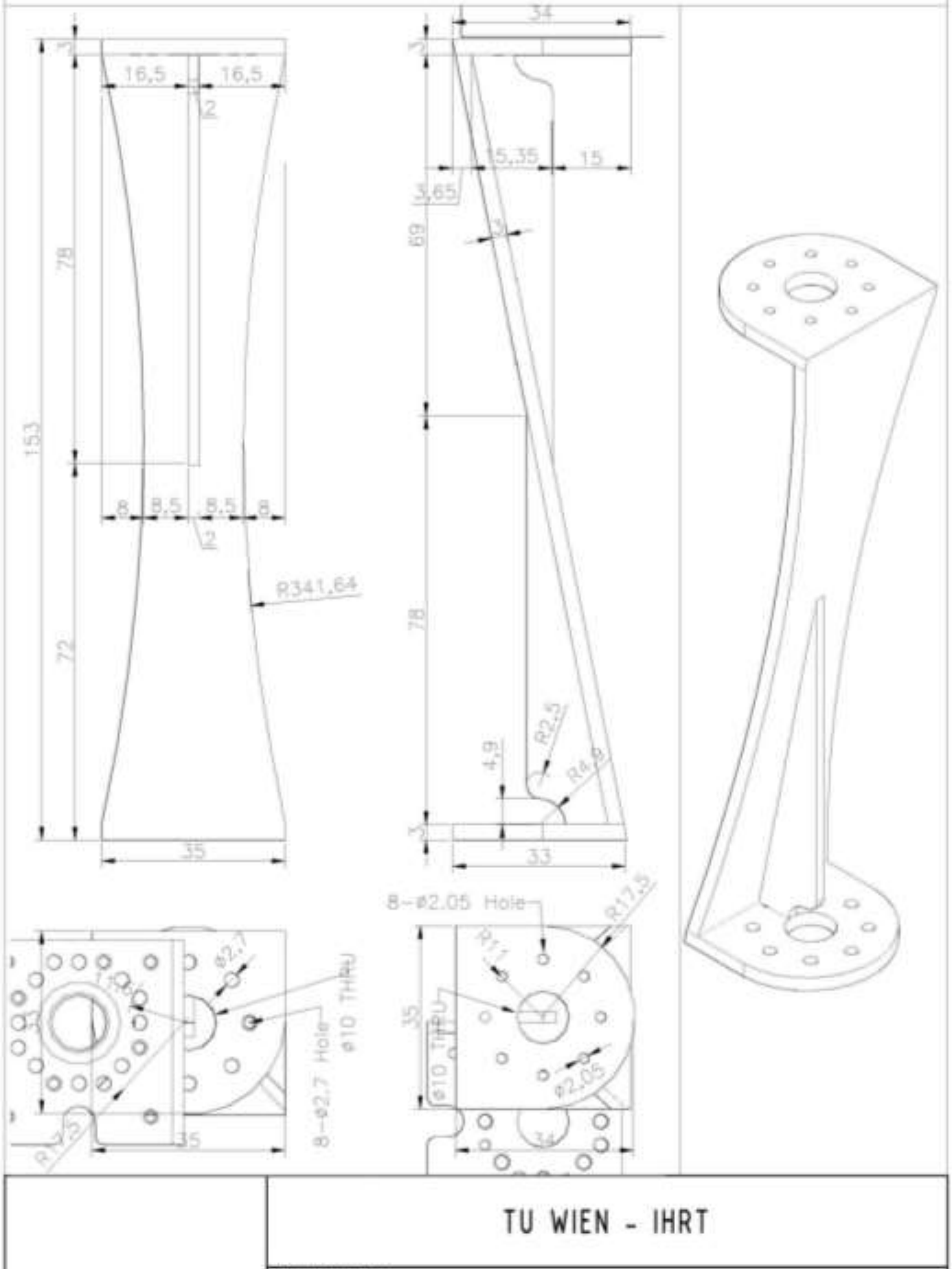
		TU WIEN - IHRT					
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE RX-64 Dynamixel Robot Servo Actuator					
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 1006				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	3/16

(2) FR05-H1(OF-64H)

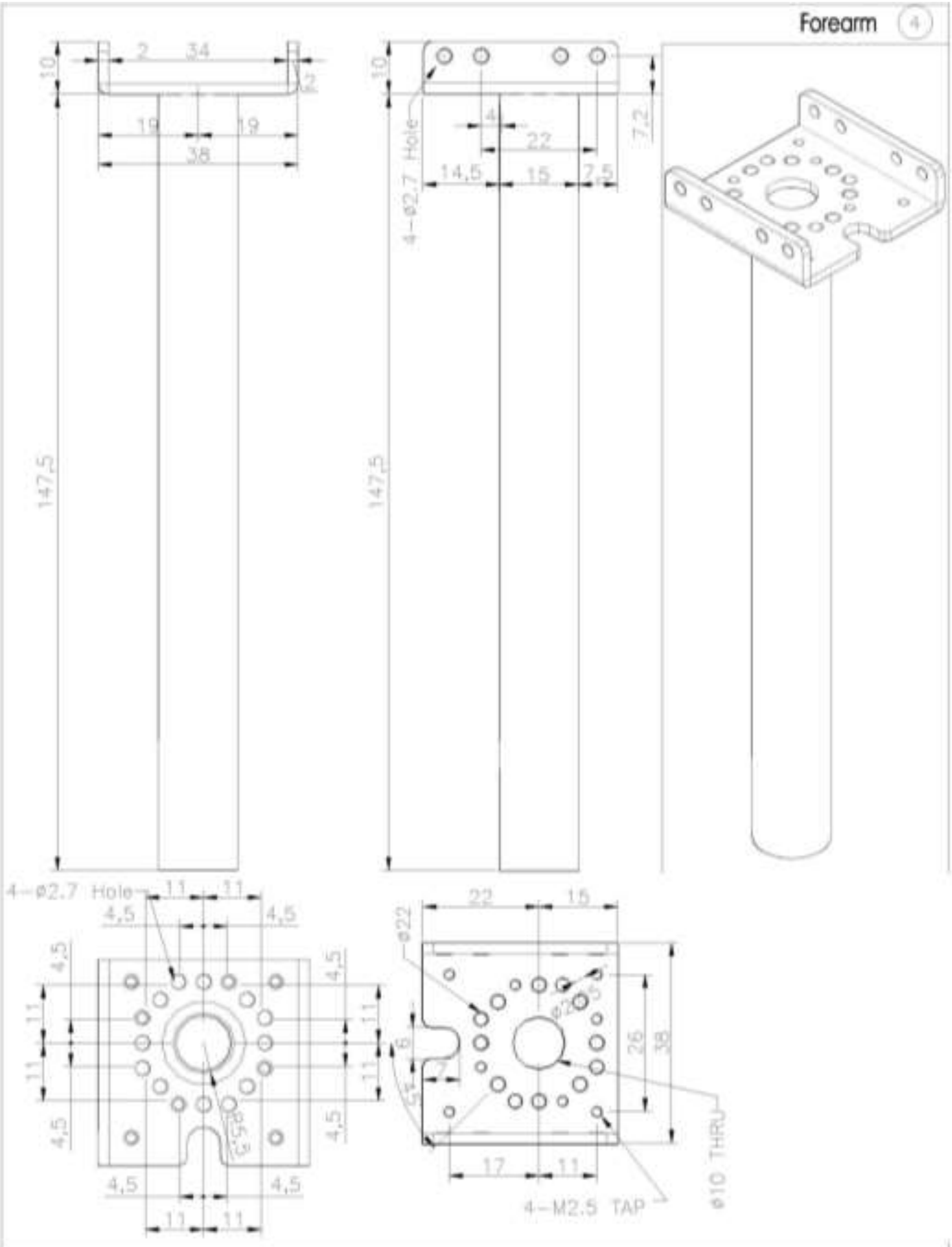


		TU WIEN - IHRT					
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE FR05-H1(OF-64H)					
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 1007				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	4/16

(3) Arm

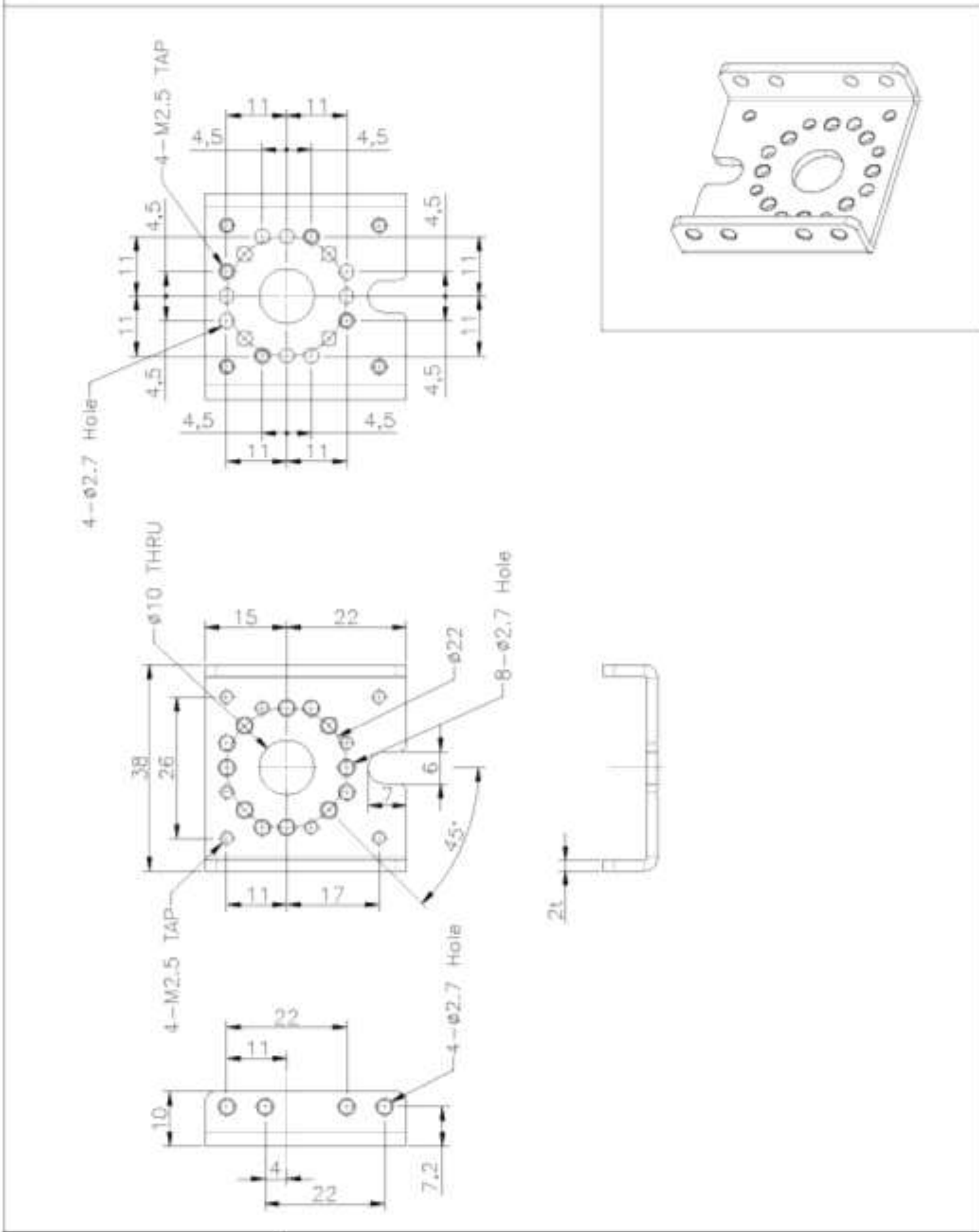


		TU WIEN - IHRT					
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE Arm					
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 1008				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	5/16



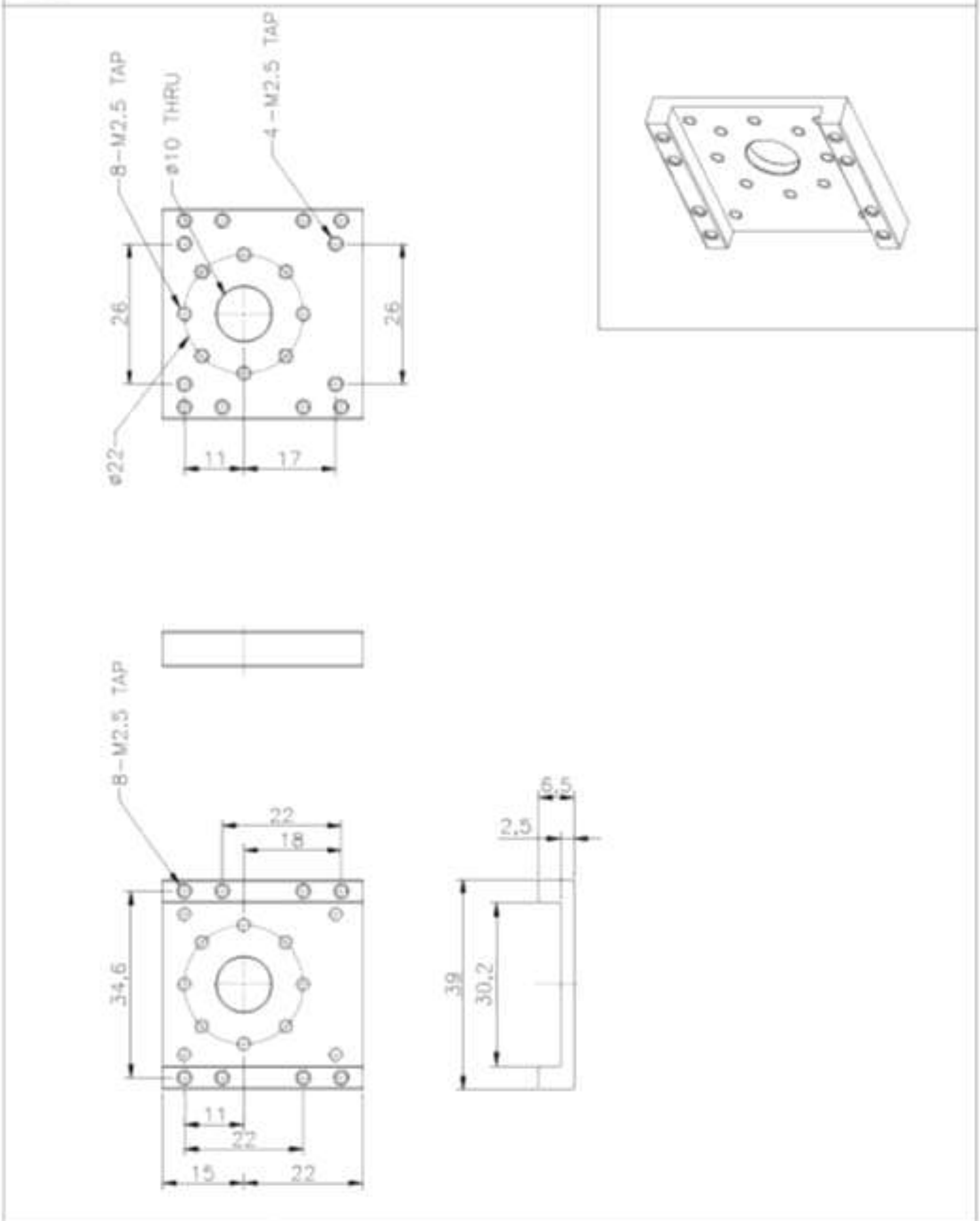
		TU WIEN - IHRT					
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE Forearm					
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 1009				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	6/16

(5) FR05-S1(OF-64S)



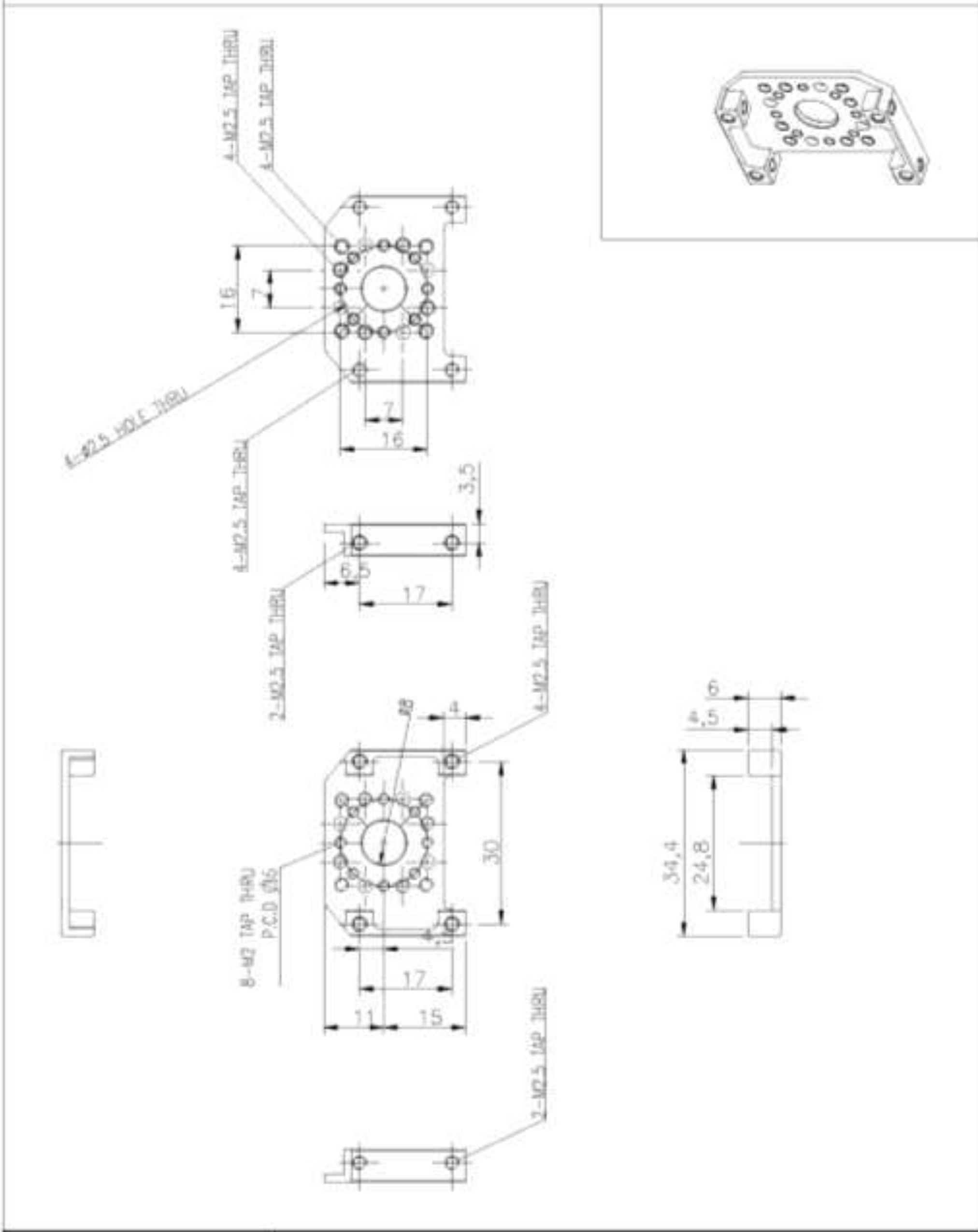
		TU WIEN - IHRT					
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE FR05-S1(OF-64S)					
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 1010				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	7/16

(6) FR05-B1(OF-64B)

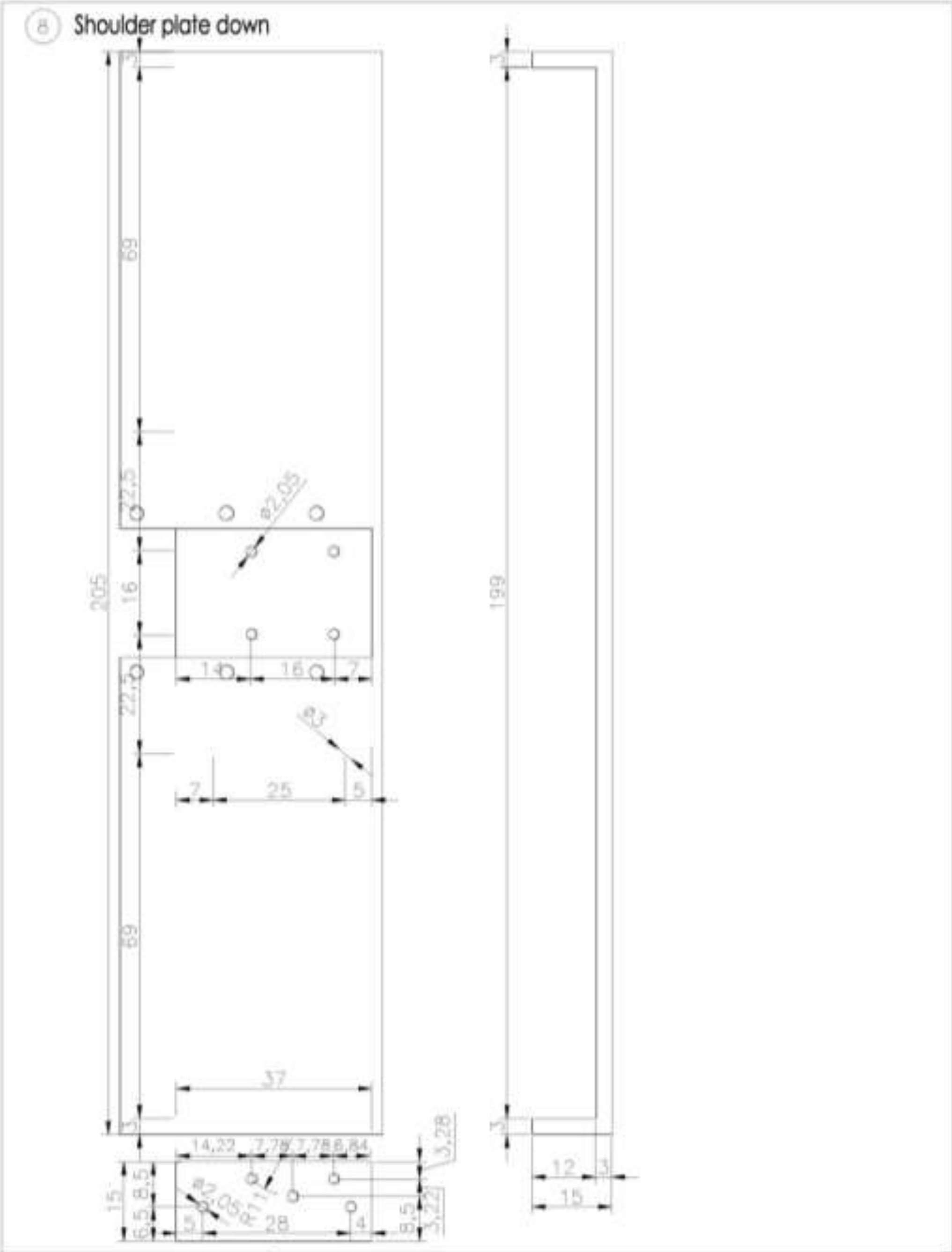


		TU WIEN - IHRT			
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE FR05-B1(OF-64B)			
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 1011		REV 1
DESIGNED BY -	DATE	SCALE 1:1	WEIGHT (kg) -		SHEET 8/16

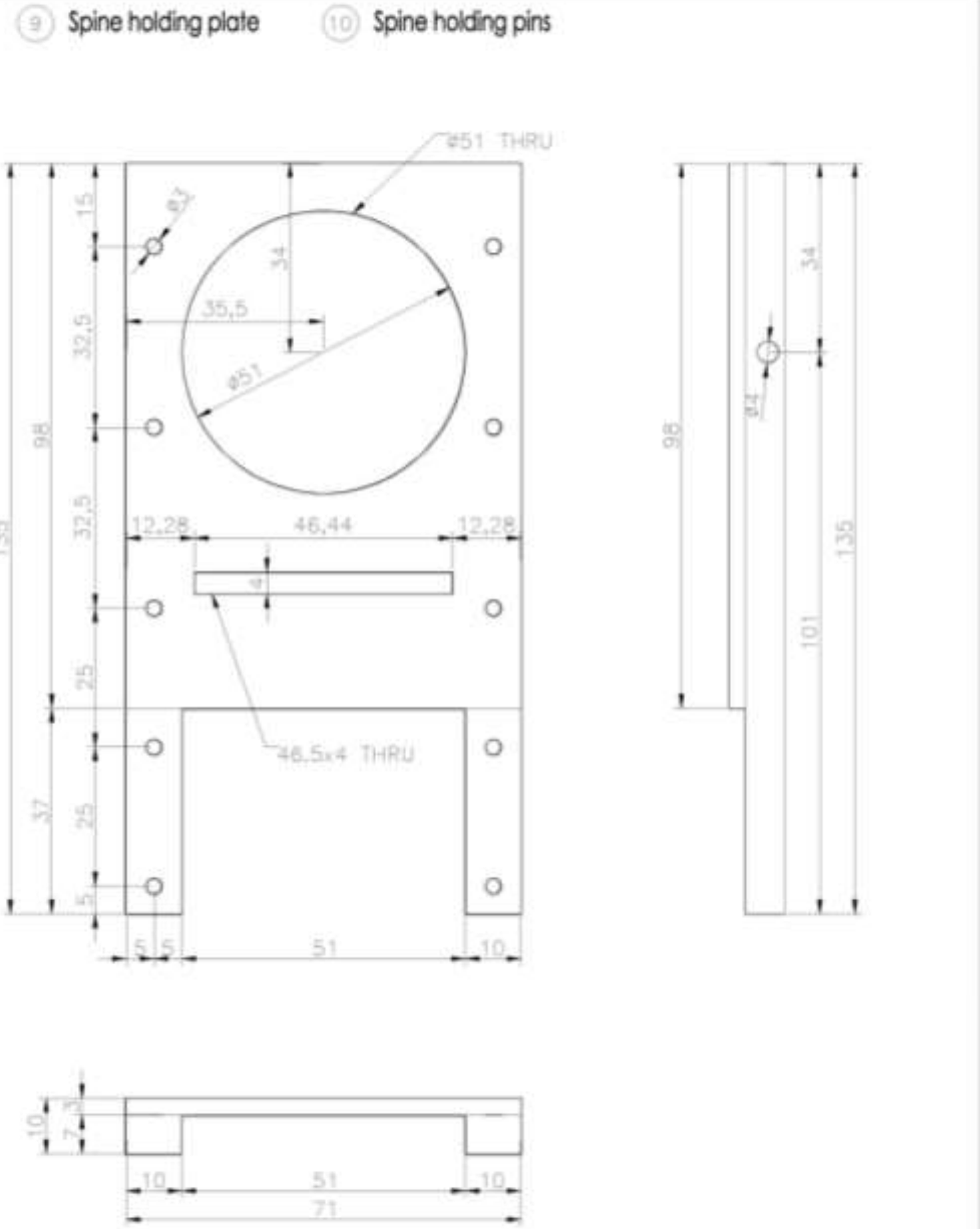
(7) FR07-B101 (RX-28)



		TU WIEN - IHRT					
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE	FR07-B101 (RX-28)				
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER	1012		REV 1	
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	9/16

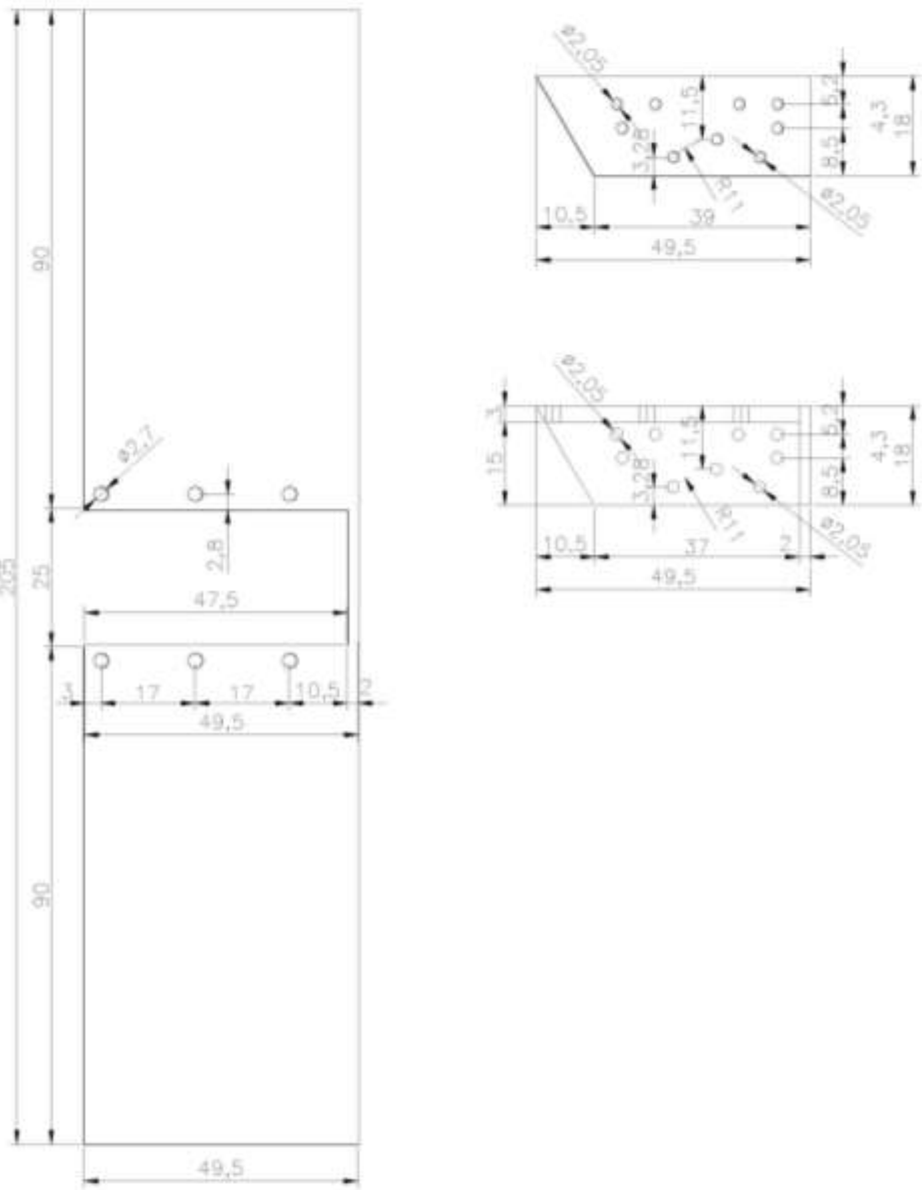


		TU WIEN - IHRT					
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE Shoulder plate down					
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 1013				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	10/16



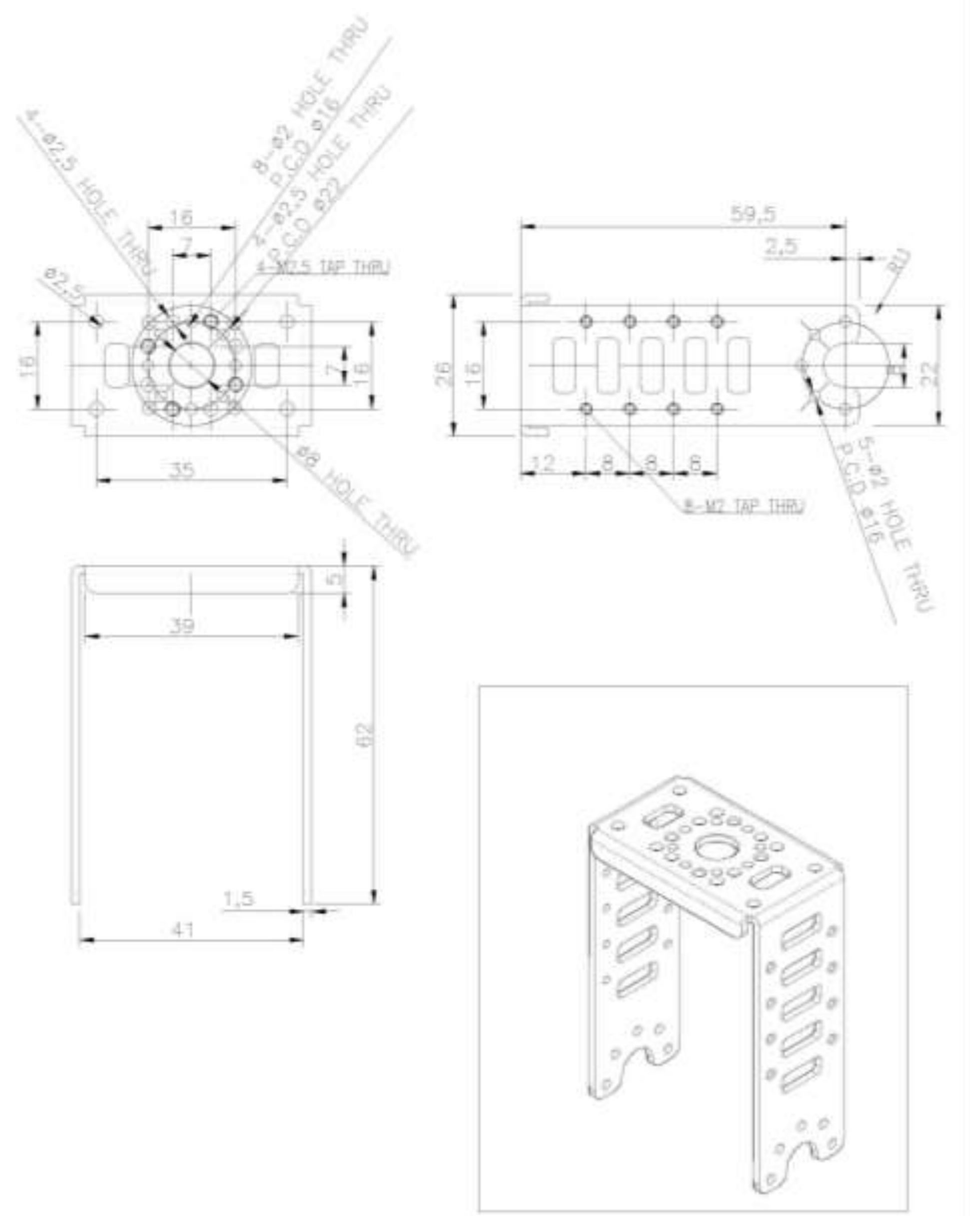
		TU WIEN - IHRT					
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE Shoulder plate down					
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 1014				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	11/16

(11) Shoulder plate up



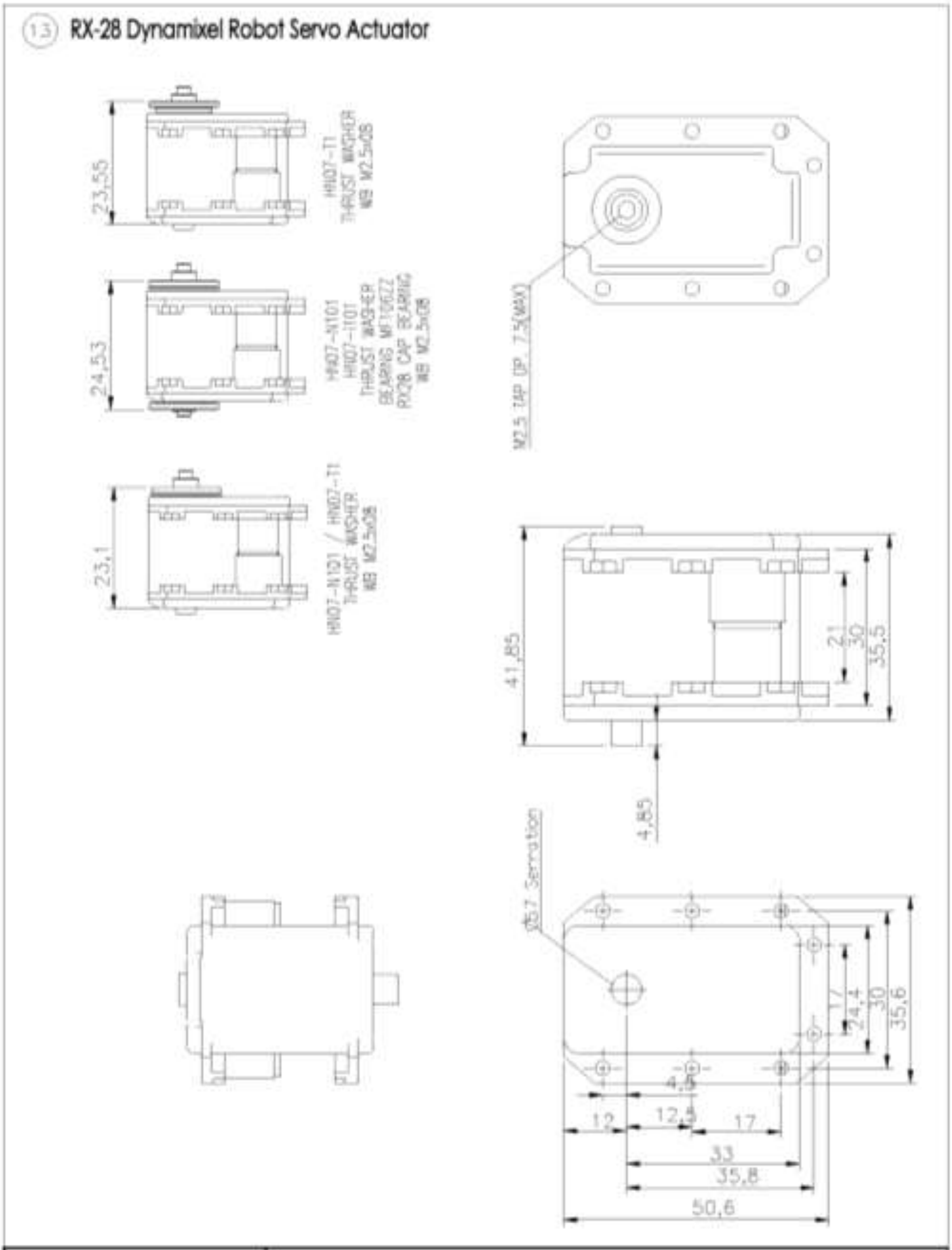
		TU WIEN - IHRT						
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE Shoulder plate up						
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 1015					REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-		SHEET	12/16

(12) Modified FR07-H101 (RX-28)



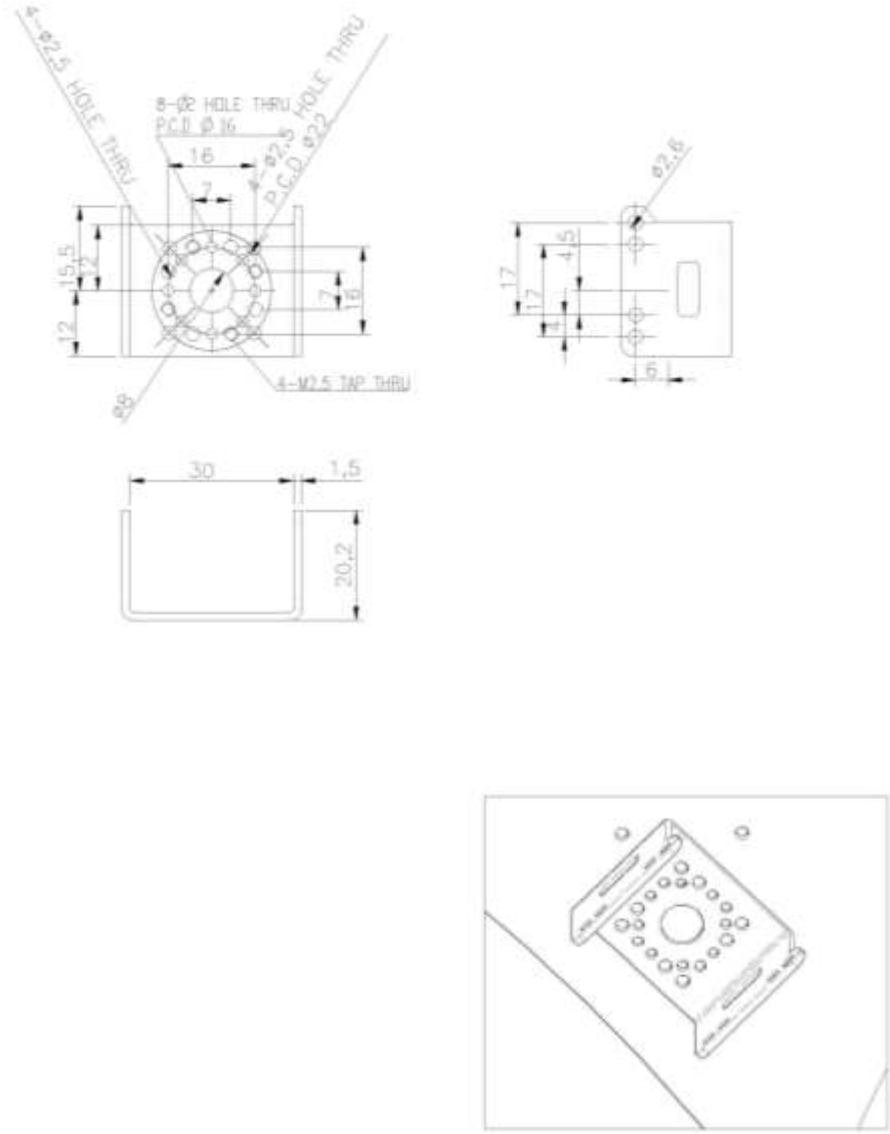
	TU WIEN - IHRT					
DRAWN BY: AS	DATE: 28.07.2016	DRAWING TITLE: Modified FR07-H101 (RX-28)				
CHECKED BY: -	DATE	SIZE: A4	DRAWING NUMBER: 1016			REV: 1
DESIGNED BY: -	DATE	SCALE: 1:1	WEIGHT (kg): -		SHEET	13/16

17.5 Motor RX-28 Dynamixel for Neck (V3)



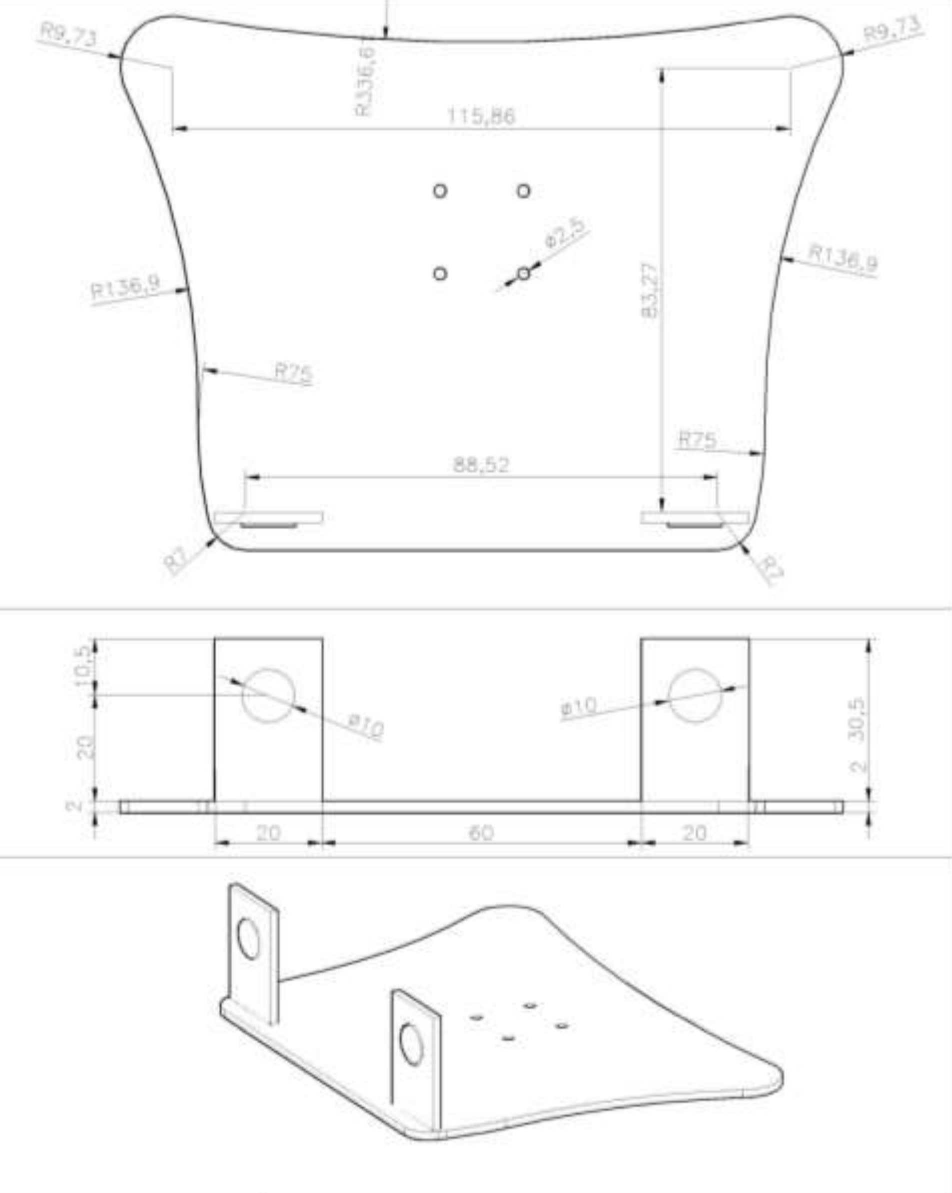
		TU WIEN - IHRT					
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE RX-28 Dynamixel Robot Servo Actuator					
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 1017				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	14/16

(14) Modified FR07-S101 (RX-28)



		TU WIEN - IHRT					
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE	Modified FR07-S101 (RX-28)				
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 1018				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	15/16

(15) Camera plate



		TU WIEN - IHRT					
DRAWN BY AS	DATE 28.07.2016	DRAWING TITLE Camera plate					
CHECKED BY -	DATE	SIZE A4	DRAWING NUMBER 1019				REV 1
DESIGNED BY -	DATE	SCALE	1:1	WEIGHT (kg)	-	SHEET	16/16

18 APPENDIX E- The first prototype

18.1 Mass properties of Assembly- upper body robot

Mass properties of the first prototype (V1-versione one)
The centre of mass and the moments of inertia are output in the coordinate system of upper body; mass = 3550 g (3.5 kg), volume = 1276978.42mm^3, surface area = 628034.32mm^2. Centre of mass: (X = 483.33, Y = 1203.58, Z = 1114.47) mm
Principal axes of inertia and principal moments of inertia ($g * mm^2$) taken at the centre of mass.

Ix = (0.02, 0.01, 1.00)	Px = 50495554.65
Iy = (1.00, 0.00, -0.02)	Py = 91070198.24
Iz = (0.00, 1.00, -0.01)	Pz = 140577695.62

Moments of inertia ($g * mm^2$):

a) Taken at the centre of mass and aligned with the output coordinate system.

Lxx = 91054589.61	Lxy = 60414.94	Lxz = 796748.77
Lyx = 60414.94	Lyy = 140572544.86	Lyz = 677124.29
Lyx = 60414.94	Lzy = 677124.29	Lzz = 50516314.04

b) Taken at the output coordinate system.

Ixx = 5380625713.82	Ixy = 1143676164.39	Ixz = 1059734661.12
Iyx = 1143676164.39	Iyy = 3041543593.15	Iyz = 2637656021.34
Izx = 1059734661.12	Izy = 2637656021.34	Izz = 3357605404.50

18.2 Mass properties of Arm

The centre of mass and the moments of inertia are output in the coordinate system of arm (the first prototype V1); mass = 567.36 g, volume = 200481.54mm^3, surface area = 215363.16mm^2, centre of massmm: (X = 682.02, Y = 1201.90, Z = 995.04)
Principal axes of inertia and principal moments of inertia ($g * mm^2$): Taken at the centre of mass.

Ix = (-0.02, 0.00, 1.00)	Px = 267157.96
Iy = (1.00, 0.00, 0.02)	Py = 24019259.24
Iz = (0.00, 1.00, 0.00)	Pz = 24079170.62

Moments of inertia ($g * mm^2$):

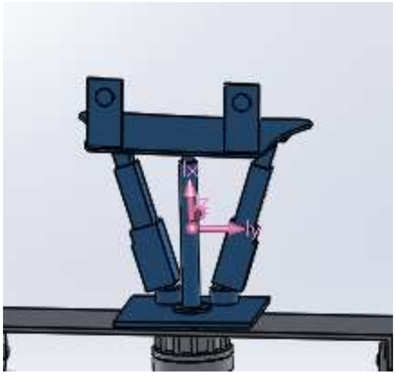
a) Taken at the centre of mass and aligned with the output coordinate system.

Lxx = 24007079.53	Lxy = 612.93	Lxz = -537723.71
Lyx = 612.93	Lyy = 24079132.39	Lyz = -30135.05
Lzx = -537723.71	Lzy = -30135.05	Lzz = 279375.90

b) Taken at the output coordinate system.

Ixx = 1405346419.77	Ixy = 465077677.86	Ixz = 384491993.96
Iyx = 465077677.86	Iyy = 849729491.02	Iyz = 678499675.81
Izx = 384491993.96	Izy = 678499675.81	Izz = 1083781544.61

18.3 Mass properties of selected components Head/Neck/Chest



Mass properties of Neck/Head V1; mass = 411.09 g, volume = 97242.86mm^3, surface area = 68488.81mm^2. Centre of mass (mm); X = 481.87, Y = 1210.83, Z = 1320.07. Principal axes of inertia and principal moments of inertia ($g * mm^2$): Taken at the centre of mass.

Ix = (-0.01, -0.20, 0.98)	Px = 459390.42
Iy = (1.00, 0.05, 0.02)	Py = 814892.09
Iz = (-0.05, 0.98, 0.20)	Pz = 985417.53

Moments of inertia: ($g * mm^2$);

a) Taken at the centre of mass and aligned with the output coordinate system.

Lxx = 815274.24	Lxy = 9125.45	Lxz = -2172.08
Lyx = 9125.45	Lyy = 964215.97	Lyz = -102407.01
Lzx = -2172.08	Lzy = -102407.01	Lzz = 480209.83

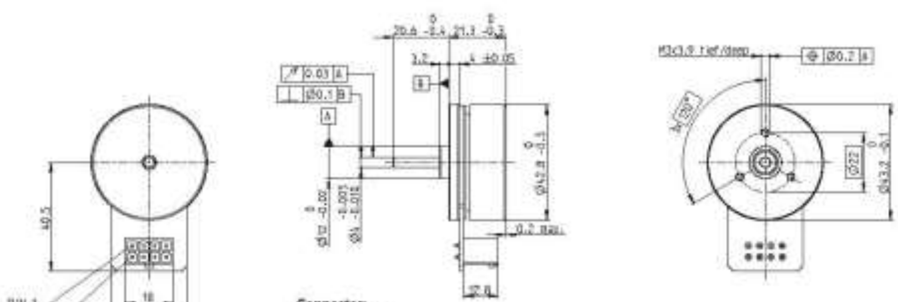
b) Taken at the output coordinate system.

Ixx = 1319884534.63	Ixy = 239863531.03	Ixz = 261491686.25
Iyx = 239863531.03	Iyy = 812780365.60	Iyz = 656979363.09
Izx = 261491686.25	Izy = 656979363.09	Izz = 698639405.04

18.4 Motors

EC 45 flat ∅42.8 mm, brushless, 50 Watt

maxon flat motor



M 1:2

- Stock program
- Standard program
- Special program (on request)

Part Numbers

with Hall sensors		339285	251601	339286	339287
Motor Data					
Values at nominal voltage					
1 Nominal voltage	V	18	24	24	36
2 No load speed	rpm	6720	6710	4730	3360
3 No load current	mA	247	185	106	42.3
4 Nominal speed	rpm	5190	5240	3480	2360
5 Nominal torque (max. continuous torque)	mNm	87.1	83.4	69.6	90.5
6 Nominal current (max. continuous current)	A	3.52	2.33	1.41	0.829
7 Stall torque	mNm	975	780	402	484
8 Stall current	A	38.8	23.3	8.47	4.81
9 Max. efficiency	%	85	83	79	82
Characteristics					
10 Terminal resistance phase to phase	Ω	0.464	1.03	2.83	7.46
11 Terminal inductance phase to phase	mH	0.322	0.572	1.15	5.15
12 Torque constant	mNm/A	25.1	33.5	47.5	101
13 Speed constant	rpm/V	380	285	201	95
14 Speed/torque gradient	rpm/mNm	7.02	8.77	12	7.07
15 Mechanical time constant	ms	9.92	12.4	17	10
16 Rotor inertia	gcm²	135	135	135	135

Specifications

Thermal data

17 Thermal resistance housing-ambient	4.53 K/W
18 Thermal resistance winding-housing	4.75 K/W
19 Thermal time constant winding	17.7 s
20 Thermal time constant motor	227 s
21 Ambient temperature	-40 ... +100°C
22 Max. winding temperature	+125°C

Mechanical data (preloaded ball bearings)

23 Max. speed	10 000 rpm
24 Axial play at axial load < 4.0 N	0 mm
> 4.0 N	0.14 mm
25 Radial play	preloaded
26 Max. axial load (dynamic)	3.8 N
27 Max. force for press fits (static)	63 N
(static, shaft supported)	1000 N
28 Max. radial load, 5 mm from flange	20 N

Other specifications

29 Number of pole pairs	8
30 Number of phases	3
31 Weight of motor	110 g

Values listed in the table are nominal.

Connection

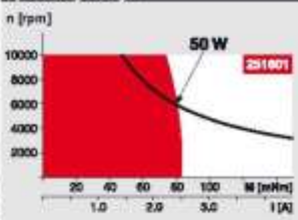
Pin 1	Hall sensor 1*
Pin 2	Hall sensor 2*
Pin 3	V_{Hall} 4.5 ... 18 VDC
Pin 4	Motor winding 3
Pin 5	Hall sensor 3*
Pin 6	GND
Pin 7	Motor winding 1
Pin 8	Motor winding 2

*Internal pull-up (7 ... 13 kΩ) on pin 3
Wiring diagram for Hall sensors see p. 35

Cable

Connection cable Universal, L = 500 mm	**339380**
Connection cable to EPOS, L = 500 mm	**354045**

Operating Range



Comments

Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

Assigned power rating

maxon Modular System

Overview on page 20–25

Planetary Gearhead
Ø42 mm
3 - 15 Nm
Page 316

Spur Gearhead
Ø45 mm
0.5 - 2.0 Nm
Page 317

Encoder MILE
256 - 2048 CPT,
2 channels
Page 342

Recommended Electronics:

	Page
Notes	**24**
ESCON Module 24/2	378
ESCON 36/3 EC	379
ESCON Mod. 50/4 EC-S	379
ESCON Module 50/5	378
ESCON 50/5	380
DEC Module 24/2	382
DEC Module 50/5	382
EPOS2 24/2	386
EPOS2 Module 36/2	386
EPOS2 24/5, 50/5	387
EPOS2 P 24/5	390
EPOS3 70/10 EtherCAT	393
MAXPOS 50/5	398

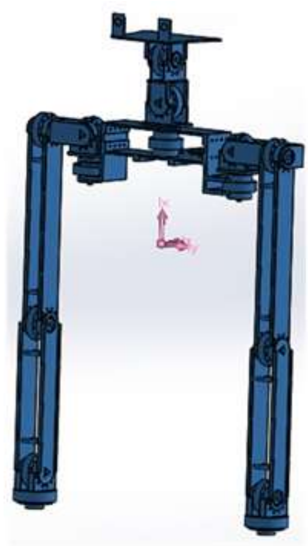
Option
With Cable and Connector
(Ambient temperature -20 ... +100°C)

262 maxon EC motor

April 2015 edition / subject to change

19 Appendix D- The second prototype

20 Mass properties of upper body



Mass = 3742.65 g (3.74265 kg), Density~2, 78 [g/cm3], Volume = 1346043.1654676mm^3, Surface area = 507418.26mm^2, Density; =2.78
Centre of mass (mm): [X = 141.62; Y = 195.63; Z = -29.38].
Principal axes of inertia and principal moments of inertia: ($g * mm^2$): Taken at the centre of mass.

Ix = (0.00, 0.02, 1.00)	Px = 81139563.36
Iy = (1.00, 0.00, 0.00)	Py = 133514338.20
Iz = (0.00, 1.00, -0.02)	Pz = 212773616.79

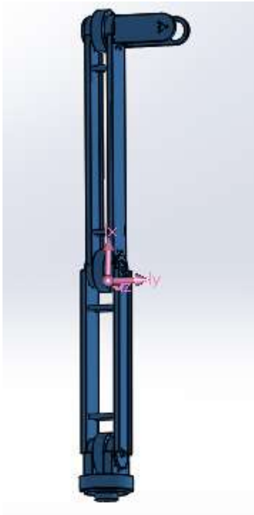
Moments of inertia, with units ($g * mm^2$), taken at the centre of mass and aligned with the output coordinate system.

Lxx = 133513216.82	Lxy = 1129.41	Lxz = -242467.72
Lyx = 1129.41	Lyy = 212718989.84	Lyz = 2680981.44
Lzx = -242467.72	Lzy = 2680981.44	Lzz = 81195311.70

Moments of inertia taken at the output coordinate system.

Ixx = 260407908.60	Ixy = 89837730.04	Ixz = -13735905.97
Iyx = 89837730.04	Iyy = 280554292.86	Iyz = -15958077.48
Izx = -13735905.97	Izy = -15958077.48	Izz = 270326141.17

20.1 Arm of Archie V2



Mass properties; Mass = 841.18 g, Density~2, 78 [g/cm3], Volume = 277589.46mm^3, Surface area = 142207.50 mm^2,.
Centre of mass: (X = -167.43, Y = 224.75, Z = -128.13) (mm)
Principal axes of inertia and principal moments of inertia, (with units$g * mm^2$): Taken at the centre of mass.

Ix = (0.02, 0.00, 1.00)	Px = 340339.70
Iy = (1.00, 0.07, -0.02)	Py = 32061476.64
Iz = (-0.07, 1.00, 0.00)	Pz = 32152649.63

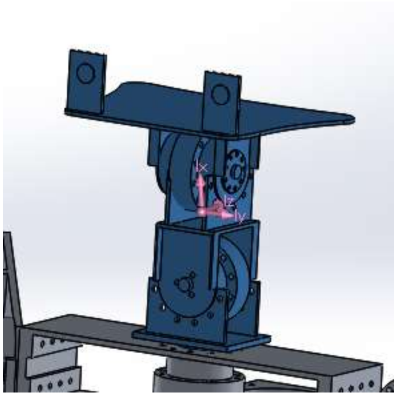
Moments of inertia: ($g * mm^2$); taken at the centre of mass and aligned with the output coordinate system.

Lxx = 32053290.82	Lxy = 5584.63	Lxz = 521924.03
Lyx = 5584.63	Lyy = 32152220.17	Lyz = -28617.91
Lzx = 521924.03	Lzy = -28617.91	Lzz = 348954.98

Taken at the output coordinate system;

Ixx = 88353941.11	Ixy = -31648150.77	Ixz = 18568413.07
Iyx = -31648150.77	Iyy = 69544226.71	Iyz = -24252988.16
Izx = 18568413.07	Izy = -24252988.16	Izz = 66419921.88

20.2 Mass properties of total Neck /Head;



Mass = 398.33 g, Density~2, 78 [g/cm3], volume = 127655.81mm^3, Surface area = 74071.93mm^2.
Centre of mass; (X = -68.74, Y = 56.41, Z = 409.48) (mm)
Principal axes of inertia and principal moments of inertia: ($g * mm^2$). Taken at the centre of mass.

Ix = (0.00, -0.10, 0.99) Px = 221679.40
Iy = (1.00, 0.00, 0.00) Py = 719347.13
Iz = (0.00, 0.99, 0.10) Pz = 735788.32

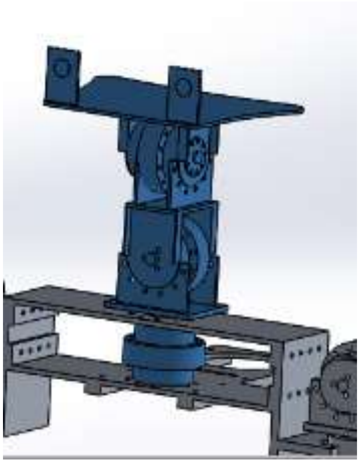
Moments of inertia ($g * mm^2$):
Taken at the centre of mass and aligned with the output coordinate system.

Lxx = 719347.17	Lxy = 22.00	Lxz = 174.10
Lyx = 22.00	Lyy = 730152.83	Lyz = -53529.87
Lzx = 174.10	Lzy = -53529.87	Lzz = 227314.85

Moments of inertia ($g * mm^2$): Taken at the output coordinate system.

Ixx = 68775547.94	Ixy = -1544440.57	Ixz = -11211181.98
Iyx = -1544440.57	Iyy = 69400844.27	Iyz = 9147201.61
Izx = -11211181.98	Izy = 9147201.61	Izz = 3376768.33

20.2.1 Mass properties of Neck /Head with three motors;



Mass properties of Neck/Head; mass = 528.33 g, volume = 167042.95mm^3, surface area = 83622.86mm^2, centre of mass (mm); X = 140.15, Y = 197.07, Z = 174.87.
Principal axes of inertia and principal moments of inertia ($g*mm^2$): Taken at the centre of mass.

Ix = (-0.04, -0.06, 1.00)	Px = 250251.06
Iy = (1.00, -0.03, 0.04	Py = 1547791.22
Iz = (0.03, 1.00, 0.06)	Pz = 1562687.94

Moments of inertia ($g*mm^2$):
Taken at the centre of mass and aligned with the output coordinate system.

Lxx = 1545721.68	Lxy = 2505.11	Lxz = -51862.24
Lyx = 2505.11	Lyy = 1558541.58	Lyz = -73492.44
Lzx = -51862.24	Lzy = -73492.44	Lzz = 256466.97

Moments of inertia ($g*mm^2$): Taken at the output coordinate system.

Ixx = 38219533.62	Ixy = 14594090.45	Ixz = 12895975.17
Iyx = 14594090.45	Iyy = 28091175.37	Iyz = 18133225.10
Izx = 12895975.17	Izy = 18133225.10	Izz = 31151465.69

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