

# **Motion Capture to the People:**

A High Quality, Low Budget Approach to Real Time  
Motion Capture

Daniel Saidi<sup>\*</sup>

Magnus Åsard<sup>†</sup>

Master's Thesis in Media Technology

March 3, 2005

Department of Science and Technology  
Linköping Institute of Technology  
Linköpings Unversitet

---

<sup>\*</sup> daniel@saidi.se

<sup>†</sup> magnus.asard@gmail.com

# **Abstract**

Motion Capture is currently a widely used technology for character animation, and can be seen as a common ingredient of many contemporary animated feature films and video games. Compared to traditional character animation, the Motion Capture technology can quickly produce very high quality animation data with high resemblance to real life motion. Unfortunately, the technology is very expensive, and commercial systems with a price tag below \$20,000 can today be considered as a bargain. Hence, using Motion Capture as a tool for incorporating high quality live motion in a low budget animation project seems impossible as of today.

However, since the underlying theory and principles behind capturing live motion are relatively straightforward, it should be possible to develop a Motion Capture system without having to spend tens of thousands of dollars. This thesis presents a full body Motion Capture system developed with strictly limited resources, at a total cost of \$950. The system consists of an electromechanical, exoskeletal suit, constructed with cheap and lightweight materials, and a client-server software solution capable of real time visualization and data export.

This diploma work has shown that it is possible to construct a high quality, real time Motion Capture system at a considerably low cost, compared to commercial alternatives. By offering blueprints for mechanics, schematics for electronics and source code for the software solution, this project opens doors for further development by other technical institutions and hobbyists.

## **Acknowledgements**

We would like to thank our supervisor, Dr. Stefan Gustavson, and Sven Franzén at the Department of Science and Technology at Linköping Institute of Technology for their help and support during this diploma work.

# Table of Contents

1.	Introduction.....	1
1.1.	Motivation.....	1
1.2.	Problem Description.....	1
1.3.	Objectives.....	2
1.4.	Method.....	3
1.5.	Limitations.....	3
1.6.	Thesis Outline.....	3
2.	Background and Related Work.....	4
2.1.	Motion Capture Technologies.....	4
2.1.1.	Optical Systems.....	4
2.1.2.	Electromagnetic Systems.....	6
2.1.3.	Electromechanical Systems.....	7
2.1.4.	Other Systems.....	8
2.2.	The Monkey.....	8
2.3.	Technology discussion.....	9
3.	Implementation.....	11
3.1.	System Pipeline.....	11
3.2.	Mechanics.....	13
3.2.1.	Materials.....	13
3.2.2.	Gimbal Lock.....	14
3.2.3.	Limbs.....	15
3.2.4.	Blocks and Plugs.....	16
3.2.5.	Profiles.....	17
3.2.6.	Supportive Pads.....	18
3.3.	Electronics.....	18
3.3.1.	Potentiometers.....	18
3.3.2.	Computer Interface.....	19
3.3.3.	Circuitry.....	19
3.3.4.	Wiring.....	20
3.4.	Software.....	21
3.4.1.	Overview.....	21
3.4.2.	Server Software.....	22
3.4.3.	Calibration.....	22
3.4.4.	Client Software.....	23
3.4.5.	BVH File Exporter.....	24
3.4.6.	Technical Specifications.....	24
4.	Results.....	25
4.1.	Mechanics.....	25
4.2.	Electronics.....	29
4.3.	Software.....	30
4.3.1.	Server Software.....	30
4.3.2.	Client Software.....	31
4.4.	Capture Examples.....	32
4.5.	Hardware Cost.....	34
5.	Discussion.....	35
5.1.	Conclusions.....	35

5.2.	Future Work.....	35
5.3.	Applications .....	36
6.	References .....	38
6.1.	Books .....	38
6.2.	Articles & Papers.....	38
6.3.	Internet .....	38
7.	Appendix A - Electronic Schematics .....	40
8.	Appendix B - BVH Example File.....	41
9.	Appendix C - Mechanical Blueprints .....	43

## Table of Figures

Figure 2.1: In optical systems, several camera sensors track visual marker sources placed on the tracked subject. ....	5
Figure 2.2: In electromagnetic systems, body-placed sensors are moved within an electromagnetic source field. ....	6
Figure 2.3: In electromechanical systems, body-placed sensors are placed at major joints and used to detect limb rotations. ....	7
Figure 2.4: Action shot of Gustavson's Monkey prototype. ....	9
Figure 3.1: Illustration of the proposed system pipeline. Motion data from the exoskeleton is sent to the central computer via an electronic unit. Client computers can then connect to the central computer and retrieve the motion data. ....	12
Figure 3.2: Overview of the head joint. ....	12
Figure 3.3: Gimbal Lock is the result of axis alignment, which may cause the joint to twist and lock into place. ....	14
Figure 3.4: Limb of exoskeleton contracted due to arm abduction. ....	15
Figure 3.5: Rotating and sliding telescope vs. a version locked from rotation and a completely locked one. ....	16
Figure 3.6: Two different designs of potentiometer blocks. ....	16
Figure 3.7: Two different designs of potentiometer plugs. ....	16
Figure 3.8: Robust profile with both ends fixed. ....	17
Figure 3.9: Robustness increased by careful design. ....	17
Figure 3.10: Blocked limb rotation vs. bad limb displacement. ....	18
Figure 3.11: Illustration of BI Technologies precision potentiometer, model 6187. The CW and CCW terminals connects to voltage and ground input respectively. The S terminal is signal output. ....	19
Figure 3.12: Illustration of resistor and capacitor placement at each potentiometer, with parallel connected voltage and ground inputs. ....	20
Figure 3.13: Data flow of the client-server solution. ....	22
Figure 3.14: Example of hierarchical data initially sent from the server to the client, describing the skeletal setup of the current user. The Depth field indicates the relationship of the current node with respect to its parent. A value of -1 in one or more of the Channel fields indicates that the current joint has no rotation in the specific direction. ....	23
Figure 4.1: While the initial potentiometer setup, shown to the left, corresponds to the joint characteristics of a human body, the rightmost has been configured to avoid Gimbal Lock and provide better rotational response. The numbers indicate the DOF at each joint. ....	25
Figure 4.2: Performer wearing the full body exoskeleton. ....	26
Figure 4.3: Exoskeleton parts. ....	27
Figure 4.4: The three upper spine joints - upper chest, neck and head. ....	28
Figure 4.5: Close-up of the head and neck joints. ....	28
Figure 4.6: Close-up of the arm. ....	29
Figure 4.7: Close-up of the leg. ....	29
Figure 4.8: Illustration of possible collar bone solution. ....	29
Figure 4.9: Electronic unit attached to the rear pads. ....	30
Figure 4.10: Server software GUI. ....	31

Figure 4.11: Client software GUI.....	32
Figure 4.12: Live performance, real time visualization, 3D Studio Max Biped and 3D Studio Max render. ....	33

# **1. Introduction**

This thesis is the result of a diploma work carried out at the Department of Science and Technology at Linköping Institute of Technology from September 2004 until March 2005. It serves as a fulfillment of a Master of Science degree in Media Technology.

## **1.1. Motivation**

Motion Capture is currently a widely used technology for character animation, and can be seen as a common ingredient of many contemporary animated feature films and video games. Compared to traditional character animation, which is often a difficult process that takes trained artists long time to manually position the character, the Motion Capture technology can quickly produce very high quality animation data with high resemblance to real life motion. Thus, as the demands on computer graphics and special effects are increasing, Motion Capture serves as a convenient and convincing way of taking character animation to a whole new level.

However, the Motion Capture process is not as straightforward and simple as it may seem. Foremost, there are a wide variety of commercial systems to choose from, where companies such as Meta Motion [5] and Motion Analysis Corporation [6] offer highly advanced systems for real time Motion Capture. Still, from the perspective of a general user or a hobbyist, none of these systems are even remotely affordable, and a full body Motion Capture system with a price tag below \$20.000 can today be considered as a bargain. Of course, the main target clientele for these high-end systems are big, commercial animation studios and movie production companies, with budgets accordingly. Hence, using Motion Capture as a tool for incorporating high quality live motion in a low budget animation project seems impossible as of today.

With this in mind, there is clearly a need for a simpler and much cheaper way of making Motion Capture an integral part of any animation project with limited resources. Even though most commercial high-end systems are very advanced, the underlying theory and principles behind capturing live motion are fairly straightforward and intuitive. Hence, there should be some way of developing a Motion Capture system without having to spend tens of thousands of dollars.

## **1.2. Problem Description**

The problem of developing a Motion Capture system is manifold. First of all, there are a number of tracking technologies that can be utilized to capture live motion, as will be described in Chapter 2. One of these technologies has to be



chosen for the system to be implemented. Furthermore, the system has to produce high quality data, with little or no noise.

To make the system reliable and of high quality, it has to be constructed in a robust way. At the same time, the mechanics of the system has to be comfortable to wear, since it may be worn by a performer for long periods of time. Once the actual motion data has been captured, it also has to be handled in some way to facilitate the actual use of it. For this purpose, some appropriate software needs to be implemented.

Another desired property of a high quality Motion Capture system is for it to work in real time. I.e., there has to be a small or no time delay between the actual data capture and the visual feedback.

Finally, there is also an overall desire to keep the system as simple and low cost as possible. Thus, the real problem is to combine these important criteria with the earlier mentioned desired properties. For example, due to the need of the mechanics being comfortable to wear, robustness may have to be somewhat sacrificed.

### **1.3. Objectives**

Given the above motivation and problem description, the following objectives for this thesis were decided:

- Construct a full body Motion Capture system.
- The system should be of high quality, robust and comfortable to wear.
- Implement a software solution capable of real time visualization and Motion Capture data export.
- The software implementation should make use of free/Open Source development tools and libraries to further reduce the development cost.
- Make the system solution freely available as part of the GNU General Public License, or some other equivalent non-commercial license.
- The budget for the system must not exceed \$1500.

The last objective would increase the possibility for this project to come to actual use. By releasing the whole system, including the electronic and mechanical schematics, under a non-commercial license, anyone with the appropriate technical competence would be able to make his/her own version of the system, thus making improvements and refinements of the initial solution. As a result of that, no commercial effort would be put into this project.

## **1.4. Method**

As a first step, initial effort was put into examining already existing Motion Capture systems, especially regarding the mechanical design. From that point, a lengthy process of designing the actual mechanics of the system began, including testing and evaluation of materials and components. Before the final mechanical solution was constructed, a simple but functional prototype was made. The software has been developed continuously throughout the project.

## **1.5. Limitations**

In addition to the previously mentioned objectives, the desired system has been limited to not include absolute positional reference. Three dimensional absolute positioning is a big practical difficulty that requires expensive hardware and/or a large amount of stationary sensors that would make the system virtually non-portable. Because of the budget limitations set up at the beginning of the project, absolute positional reference was to be considered as a future improvement of the system.

## **1.6. Thesis Outline**

This report is divided into five main parts. Chapter 2 will cover the relevant background and related work in the field of Motion Capture. Chapter 3 describes the conceptual idea and pipeline of the system, as well as the extensive implementation phase. In Chapter 4, results are presented, followed by a discussion in Chapter 5, where also suggestions to future work and applications are presented.

To fully grasp all concepts covered in this report, basic knowledge in computer graphics, microcomputers, electronics and programming is required.

## 2. Background and Related Work

This chapter will describe different technologies that are available for capturing live motion. For each technology, a brief description of system setup, advantages and disadvantages will be presented, as well as examples of commercial systems using the technology in question.

Since each technology has its own pros and cons, the chapter will end with a discussion on why the technology being used in this project was chosen.

### 2.1. Motion Capture Technologies

Motion Capture is the process of capturing live motion by tracking a number of key points on the tracked subject over time, translating the motion into a digitized representation of the performance. The key points can be tracked in a number of ways, but should be placed in a way that best responds to the performance of interest. For instance, while tracking human motion, the markers should be placed at the joints or limbs, depending on the system being used.

Motion Capture systems can either be of *outside-in*, *inside-out* or *inside-in* types, hinting at how *sensors* and *sources* are used for the technology in question. In outside-in systems, external sensors are used to track body-placed sources, while inside-out uses body-placed sensors and external sources. Inside-in systems have both sensors and sources placed on the tracked subject.

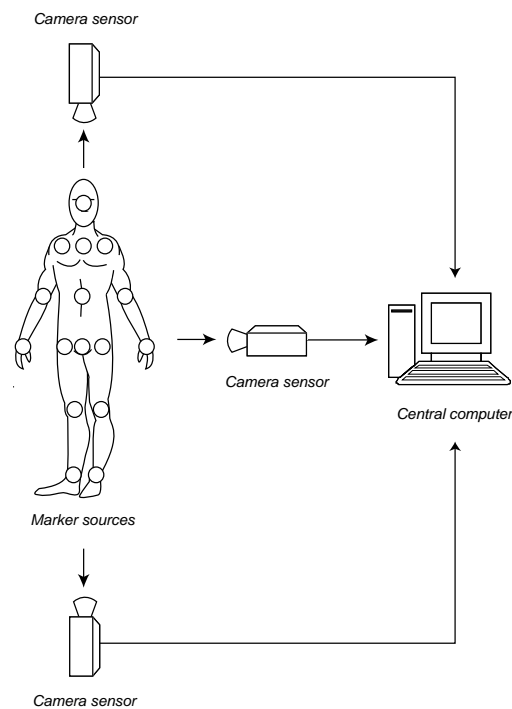
Finally, while the whole process of bringing a character to life is called *Performance Animation*, this report will refer to both steps as Motion Capture.

#### 2.1.1. Optical Systems

Optical Motion Capture is an outside-in technology that uses several camera sensors to track visual marker sources placed on the tracked subject, finally combining all the two-dimensional data into a three-dimensional Cartesian representation (x, y, z) of the motion.

While early optical systems demanded visible markers, modern ones are able to track a large number of small markers invisible to the human eye. This makes post processing much easier, since no effort has to be put into removing visible markers in cases where the performer will be visible in the final result, for example in motion pictures.

Optical systems can be highly accurate, depending on camera/marker setup. Another big advantage is that the technology does not restrict the performer's movement, since the markers are most often applied by paint or pre-marked suits. Thus, no cables have to be used.



*Figure 2.1: In optical systems, several camera sensors track visual marker sources placed on the tracked subject.*

Still, although being a very robust technology with high sample rate, a major drawback of optical systems is that real time Motion Capture is very hard to achieve, since all two-dimensional camera views must be combined and re-calculated into a three-dimensional representation of the scene for each frame. Adding the fact that higher accuracy requires more cameras, the calculation time increases for each new added view.

Another big limitation of this technology is its sensitivity to occlusion. Occluded markers can ruin the entire Motion Capture session since the system may lose information about where they belong in the scene. This problem can be approached by either using more cameras to avoid occlusion or a virtual representation of the tracked subject as a reference to where the markers should be [2]. Nevertheless, handling occlusion increases the calculation time for each frame.

Finally, an optical system is far from portable since the cameras must be placed in a controlled way, preferably with ideal lighting conditions. Even though a lot of work has been done in order to make the technology independent of these factors, a lot of time and effort must often be put into post-processing.

Examples of commercial optical systems are the Vicon MX™ [7] (\$77.250), the Qualisys [8] and the Meta Motion Motion Captor™ [5].

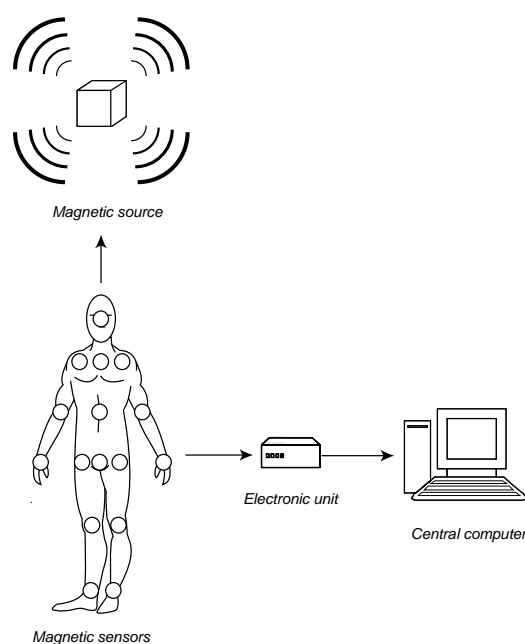
## 2.1.2. Electromagnetic Systems

Electromagnetic Motion Capture is an inside-out technology, where body-placed sensors are moved within an electromagnetic source field created by a transmitter. In a continuous process, each sensor measures its relative position to the transmitter and transmits its signal to a control unit that adjusts the signal and passes it on to a central computer, where final calculations are made.

The technology allows for six degrees of freedom (6DOF), which means that the central computer will be able to extract both Cartesian coordinates and orientation for each sensor.

Having that information available, the technology does not require as many sensors as optical systems.

A big advantage with electromagnetic systems is that the technology can be performed in real time, provided that a fairly powerful computer is used. Since most effort has to be put into signal adjustments, handled by the control unit, the computer can solely focus on the visualization. Also, if special software designed for the system in question is used, further calculations for the incoming data could be avoided.



*Figure 2.2: In electromagnetic systems, body-placed sensors are moved within an electromagnetic source field.*

Since electromagnetic sensors are under constant influence of the magnetic field, this technology has the big advantage of being one without any problems regarding occlusion. Still, the capture area is restricted to how far the electromagnetic field is extended, which usually is far more limited than its optical counterpart.

A minor drawback with the electromagnetic technology is that each sensor must be connected to the control unit, meaning that the use of many sensors requires many cables. Still, since fairly good results can be obtained using quite few sensors and wireless signal transfer between the sensors and the electromagnetic control unit can be implemented, this is not really an issue.

The major limitation with electromagnetic Motion Capture, however, is its sensitivity to external disturbances. If a magnetic field would be generated near the one created by the transmitter, for example if nearby metal objects undergo current, there is a risk that the system would experience serious interference.

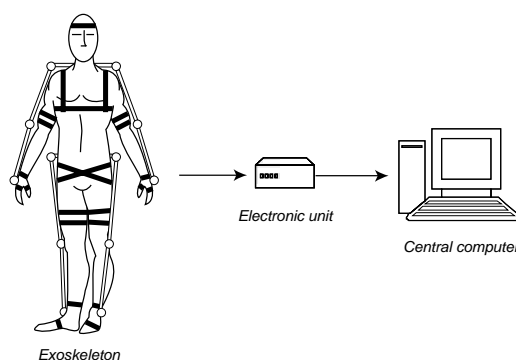
Since electromagnetic Motion Capture can use direct or alternating current, each sensitive to different types of metal, the system can be adjusted to the current metallic conditions of the surrounding. Still, since different locations have different metallic characteristics, the technology is far from portable.

Examples of commercial electromagnetic systems are the Skill Technologies 6D-Research™ [9] and the Polhemus Liberty/Patriot [10].

### 2.1.3. Electromechanical Systems

Electromechanical Motion Capture is an inside-in technology, where body-placed sensors are placed at major joints and used to detect limb rotations of the captured subject. A common approach is to use potentiometers, which vary resistance upon rotation and thus return voltages that correspond to the current rotations. These voltages are then transmitted to a central computer via an electronic unit.

Being a technology that produces angular data, electromechanical Motion Capture often requires some sort of mechanical suit to be worn in order to be able to detect rotations. One example of such a suit is the *exoskeleton*, which, as the name implies, is an external skeleton worn by the performer. During the capture process, the exoskeleton moves with the captured subject and thus gives rise to a change of voltage for the potentiometers affected by the movement.



*Figure 2.3: In electromechanical systems, body-placed sensors are placed at major joints and used to detect limb rotations.*

Electromechanical Motion Capture is a technology where performer behavior is instantly known, rapidly updated and of very high quality. Since these systems do not require any demanding calculations to be made for each frame, it can easily be performed in real time even on a fairly slow computer – a big advantage compared with previously mentioned technologies.

Furthermore, since the sensors are insensitive to external disturbance and occlusion, the technology is very portable, especially if the exoskeleton is constructed in a light and robust way. Also, as the technology involves the usage of basic electronic components and thus puts no demand on fast computers or advanced technology, it can be constructed at a very low cost.

Still, electromechanical Motion Capture suffers from the fact that a performer is bound to an exoskeleton and thus constrained by mechanics and cables. This is, of course, a question of how well the exoskeleton is constructed, and requires that a lot of effort has to be put into designing the suit in a way that

makes it comfortable to wear. The exoskeletal approach also makes it very hard to change potentiometer setup, since it involves a complete reconstruction of the affected areas. This emphasizes the need of good hardware design, since the same suit should fit performers with different body characteristics.

Finally, while optical and electromagnetic technologies can obtain the absolute position and orientation of the performer, electromechanical systems can not retrieve this information easily since they generally produce angular data. Thus, these systems may have to rely on other technologies for this purpose.

Examples of commercial electromagnetic systems are the Meta Motion Gypsy (\$20.000) [5] and the noDNA X-IST FullBodyTracker (\$34.999) [11].

#### **2.1.4. Other Systems**

While the previously described technologies are dominating the Motion Capture market, there are other technologies available as well.

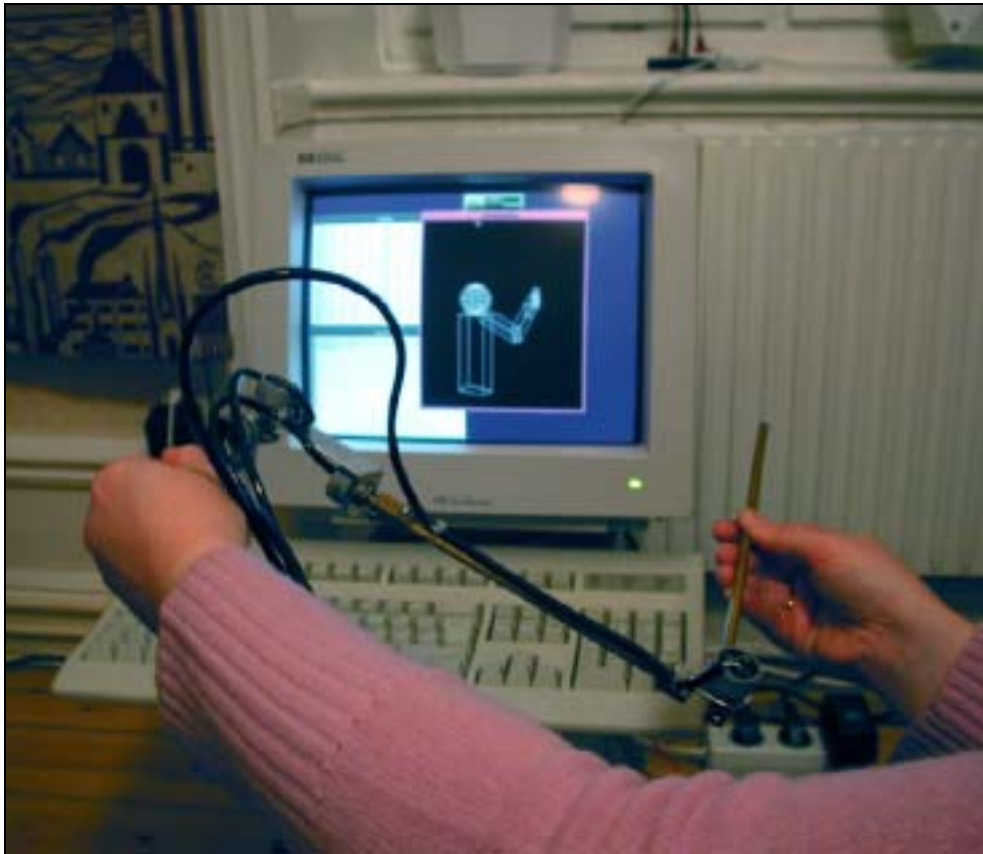
In *acoustic tracking* the captured subject wears receivers that pick up transmitter-generated ultrasound. The system detects the time difference between transmitting and receiving the impulse, using the speed of sound to calculate the location and orientation of the receivers. The system is fast and fairly cheap, but is not easily moved and suffers from error propagation.

Gyroscopes are used to perform *inertial tracking*, where the performer can be tracked very accurately while wearing a comfortable suit. Like acoustic tracking, inertial tracking suffers from propagating errors. This can be solved by combining the two technologies, like being done by the InterSense tracking systems [12], although doing so results in an even higher cost for the system.

*Accelerometers* track acceleration and can give very precise data if placed properly on the performer. Still, since position is obtained by integrating acceleration to velocity, and velocity to position, error propagation is a big issue. Furthermore, it is a very expensive technology, where a single accelerometer costs approximately \$800 [13].

## **2.2. The Monkey**

In 2002, Dr. Stefan Gustavson at the Department of Science and Technology, Linköping Institute of Technology, published a document regarding the construction of a high quality, low cost real time Motion Capture system. The project – referred to as the Monkey – resulted in an electromechanical construction with four potentiometers, capable of measuring 4DOF in real time.



*Figure 2.4: Action shot of Gustavson's Monkey prototype.*

The Monkey – not to be confused with the Monkey 2 armature constructed by Digital Image Design [14] in the 1990's – featured as a sketch presented at SIGGRAPH 2002 [3]. The prototype showed that it was possible to construct a real time Motion Capture system at a very low cost, and was then left open for further development.

The Monkey was presented at a VR course at Campus Norrköping in 2003, and although the project did not investigate the potential of modifying the suit to be worn by a performer, it seemed promising for such usage. After a discussion with Gustavson about this matter in October 2003, a decision to perform this diploma work was taken.

A complete report [4] regarding the Monkey project is available from the project website [16].

### **2.3. Technology discussion**

As previously mentioned, this diploma work started off as a continuation of the Monkey project. Although it was uncertain if the system was capable of



capturing full body motion in real time, using the same basic electronics and components, this project initially aimed at constructing such a system.

Still, since the construction of a well designed exoskeleton would be a hard task, other technologies were considered. However, due to budget concerns, all systems described in section 2.1.4 could be instantly disregarded. Even though prices have dropped during the last couple of years, constructing a full body system using either of these alternatives would require a considerably large budget.

Considering the big drawbacks of optical systems, being non-portable and expensive, it was clear that creating such a system at low cost as well as implementing algorithms to increase portability would be beyond the scope of this project. Finally, although having good potential on the real time aspect, electromagnetic tracking remained too non-portable and expensive to consider.

## 3. Implementation

This chapter will start with a description of the proposed system pipeline, and then cover the construction phase, providing detailed information about mechanics, electronics and software.

### 3.1. System Pipeline

Being an electromechanical solution, the system was planned to capture live motion by having the performer wear an exoskeleton with potentiometers placed at major joints, as described in Chapter 2. By responding to rotations, the potentiometers would supply the electronic unit with up-to-date motion data, the electronic unit finally communicating with a central computer responsible of collecting and handling the data in a suitable way.

As the Monkey project had shown that it was possible to perform electromechanical Motion Capture on a slow computer, the idea was to continue on the same track. By making real time, full body Motion Capture possible on a slow computer, the project would open doors for further improvements that could result in a small, stripped computer worn by the performer during the capture session.

Thus, the aim was to free the central computer from any unnecessary calculations, ideally having it dedicated to data acquisition and thus leaving further calculations to more powerful components. This spawned the idea of a client-server solution, where client computers connect to the server and retrieve motion data at a given rate. This would make it possible for clients to run applications that use the motion data in completely different ways. One example could be two different clients connected to the server simultaneously, one running a file exporter and the other using the data for live interaction in a virtual environment.

A schematic of the proposed system pipeline can be seen in Figure 3.1.

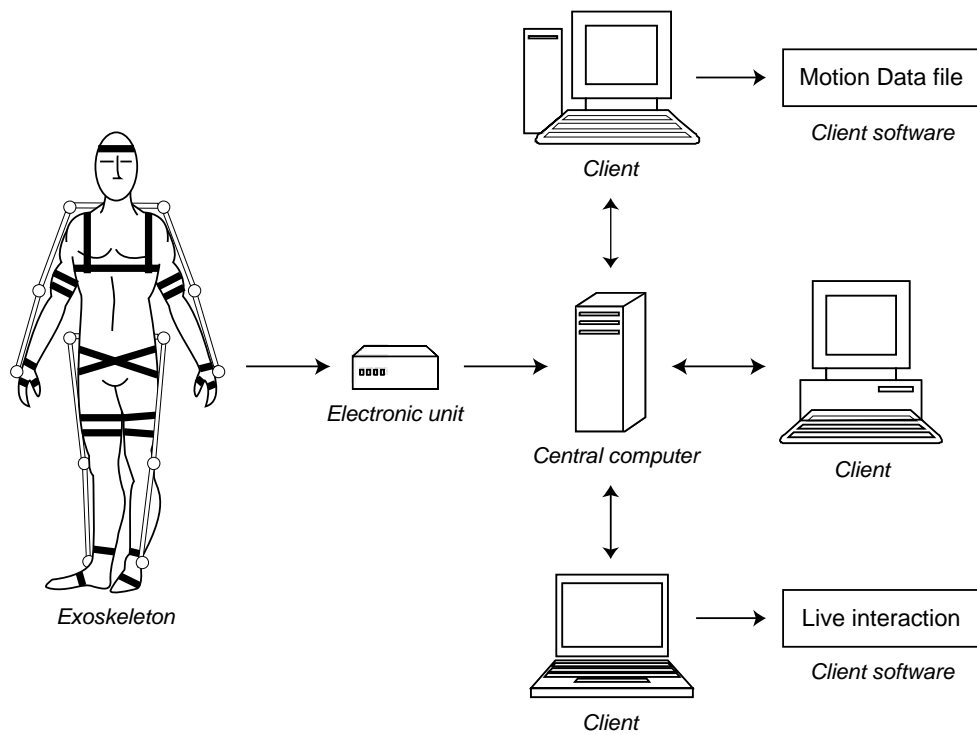


Figure 3.1: Illustration of the proposed system pipeline. Motion data from the exoskeleton is sent to the central computer via an electronic unit. Client computers can then connect to the central computer and retrieve the motion data.

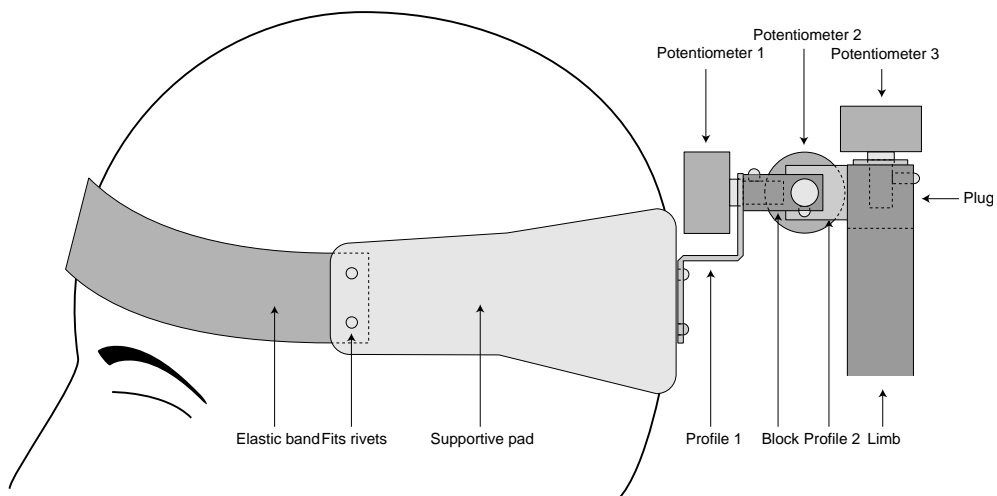


Figure 3.2: Overview of the head joint.

## 3.2. Mechanics

While having the primary goal of constructing a cheap yet comfortable exoskeleton, other desirable properties had to be defined prior to construction. For example, the exoskeleton would have to be light weighted and as free from cables as possible, as well as fairly adjustable to fit people of different body characteristics. Finally, since one of the project goals was to come up with a solution that even a hobbyist would be able to build, it had to be possible to construct the exoskeleton by using basic tools.

Figure 3.2 features an illustration of the basic exoskeletal functionality, in this case the head joint. It shows how the exoskeleton is attached to the head with a supportive pad that is tightened over the forehead with an elastic band. The entire construction is then fixed to the pad via a profile that holds Potentiometer 1 in place and is attached to the pad with fits rivets.

Furthermore, Potentiometer 1 is connected to Potentiometer 2 with a block, and Potentiometer 2 to Potentiometer 3 via a profile, thus initially placing the three potentiometers orthogonal to each other. Potentiometer 3 is then inserted into the neck limb that leads down to the next joint, and locked in place by a plug inserted at the end of the limb.

As the head is rotated, the potentiometers will rotate corresponding to the movement. While the setup in Figure 3.2 allows for 3DOF, some joints will only require 2DOF. Still, although different designs had to be done for each joint, six basic exoskeleton parts would be needed.

- *Limbs* connect two joints
- *Blocks* connect two potentiometers within a joint
- *Plugs* connect a potentiometer to a limb
- *Profiles* connect a potentiometer to a supportive pad.
- *Supportive pads* connect the exoskeleton to the body.

The following section contains a material discussion, followed by details on a problem known as *Gimbal Lock*. The chapter ends with a separate description of each part type. For further information about the mechanics, blueprints are found in Appendix C.

### 3.2.1. Materials

As each part would face its own challenges, the use of different materials for each part type had to be considered. However, by using cheap, light weight plastic where it provided the construction with the required robustness and flexibility, the overall weight and cost would be considerably reduced.

As will be explained in section 3.2.3, the limbs would have to be able to expand and contract. When deciding to approach this problem using layers of pipes, the use of either plastic or lightweight metal was considered. Still, with no metal light enough to be a suitable choice, PVC-C met the requirements since it is a light and robust plastic, fairly easy to shape. At places where further support would be needed, solid bars of PVC-C were chosen as a complement.

Although the blocks and plugs had to be robust enough to lock the potentiometers into place, they also had to be shaped for the specific use. While brass blocks were proven to work in the Monkey project, the desired shapes would be too complicated to achieve with the limited tool access. Thus, PVC-C was chosen for these parts as well.

Furthermore, the profiles had to be robust enough not to bend during use, since this would misalign the affected potentiometers and contort the motion data. Although nylon, steel or hard aluminum would have been better choices, they were too hard to shape with the available tools. Thus, softer aluminum was chosen, despite the fact that it would bend slightly.

The biggest concern regarding the supportive pads was that they had to be soft enough to fit the body comfortably, while still being robust enough to be firmly attached to the profiles. The pads should also return to an initial shape when not being used. These requirements were met by polyethane, which could be shaped after heating, fixing itself in the new shape once cooling off.

### 3.2.2. Gimbal Lock

During the construction phase, many joint designs proved not to work since they did not account for *parametric singularity* [1], more commonly known as Gimbal Lock.

Gimbal Lock may occur in joints with three or more degrees of freedom, and arises as two degrees of freedom are rotated into alignment. The joint may then rotate freely, and will thus strive for equilibrium. This may cause the joint to twist, and lock itself in place, as shown in Figure 3.3.

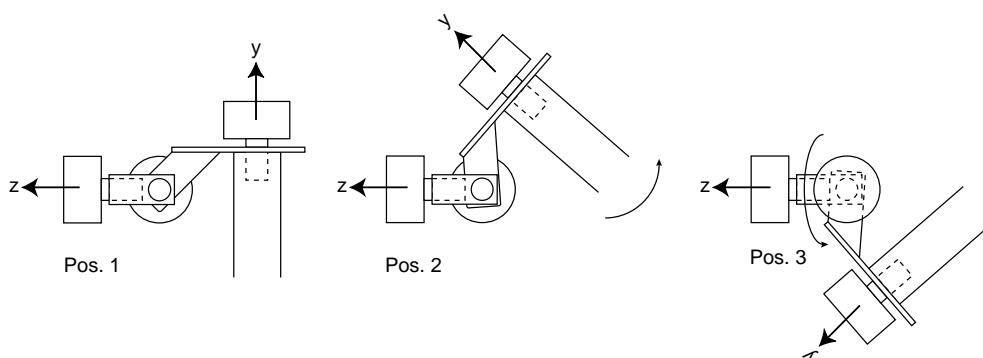
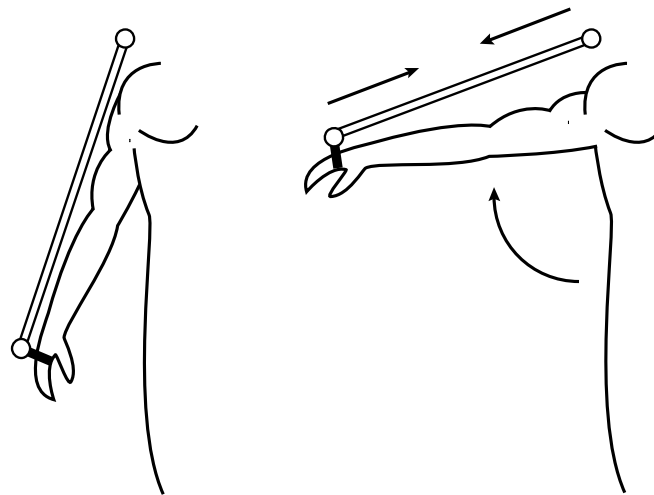


Figure 3.3: Gimbal Lock is the result of axis alignment, which may cause the joint to twist and lock into place.

As the limb rotates the rightmost potentiometer towards the leftmost one, one degree of freedom is finally lost, making the joint free to rotate as previously described. This can be partially avoided by careful joint design, like minimizing potentiometer distance in order to reduce momentum. Still, Gimbal Lock remains a big problem in electromechanical Motion Capture.

### 3.2.3. Limbs

Since the exoskeleton is worn on top of the captured body, the behavior of its limbs and the ones of the performer will differ in more ways than just their response to rotations. For example, while the limb lengths of the tracked body are more or less constant, the exoskeleton will expand and contract as its joints are translated relative to each other, as shown in Figure 3.4.



*Figure 3.4: Limb of exoskeleton contracted due to arm abduction.*

As mentioned in section 3.2.1, this problem was approached using layers of pipes to create telescopic limbs. Still, with the initial budget requirements forcing the use of industrial standard diameters, the only diameters that could be used were pipes with outer/inner diameters  $\text{Ø}20/\text{Ø}17$  mm as well as  $\text{Ø}16/\text{Ø}13.6$  mm. Moving up and down in diameter, the differences became too large to be of any use.

Although the two pipes fitted each other well, using only two layers of pipes would dramatically limit the flexibility of the telescope solution. The limb lengths thus had to be carefully dimensioned, but as some limbs would undergo a dramatic change of length during use, the flexibility problem would still be noticeable in the final result.

Instead of making the inner pipe rotate relative to the outer one, the telescopes had to be designed to have rotations in limb direction be absorbed by a

potentiometer placed at the end of the limb. This can be solved by slitting the outer pipe and fixing the inner one with a bolt. Furthermore, some limbs also had to be fixed at certain lengths, for example to fit bodies with different widths across the hips and shoulders. This can be solved by slitting the entire outer pipe and inserting a bolt through the two pipes, thus locking the inner pipe by tightening the outer one with nuts. The two solutions can be seen in Figure 3.5.

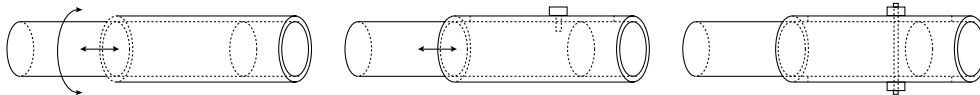


Figure 3.5: Rotating and sliding telescope vs. a version locked from rotation and a completely locked one.

### 3.2.4. Blocks and Plugs

As the blocks are used to connect the potentiometers, they had to be designed to cover the two different setups that are needed, as found in Figure 3.6 below. Still, as the second block type places the potentiometers farther away from each other than the first, thus increasing the risk of Gimbal Lock, it should only be used when no other solution is possible.

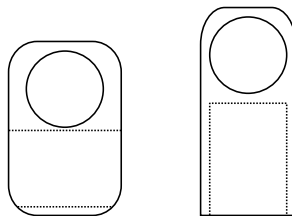


Figure 3.6: Two different designs of potentiometer blocks.

Considering the plugs, the potentiometers could either be inserted from the top or the side, resulting in the two different types shown in Figure 3.7. The plug pair would also have to be adjusted for each new pipe since they had to fit the inner diameter.

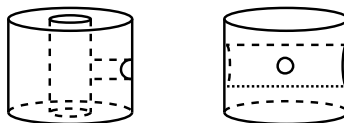
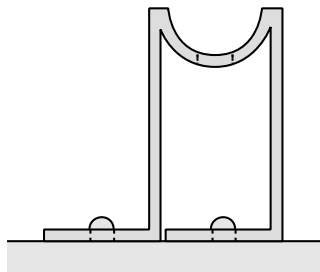


Figure 3.7: Two different designs of potentiometer plugs.

### 3.2.5. Profiles

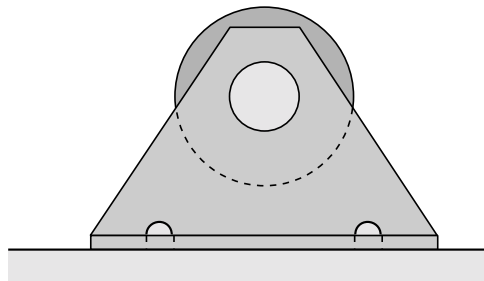
As mentioned in the material discussion, the profiles had to be as robust as possible, since a slight bend would result in incorrect motion data. By using soft aluminum, this was even more important than if a harder material would have been used. Since the exoskeleton had to be supplied with a wide variety of profiles, making each part as robust as possible would take too much time. Instead, a reasonable overall robustness would be obtained by focusing on the most critical factors, like end segments and segment lengths of the profiles.

Looking at the end segments, the profiles that could be constructed with both end segments fixed would be the most robust ones, like the one found in Figure 3.8. For such profiles, width and height could be fairly varied without the risk of weakening the profile too much.



*Figure 3.8: Robust profile with both ends fixed.*

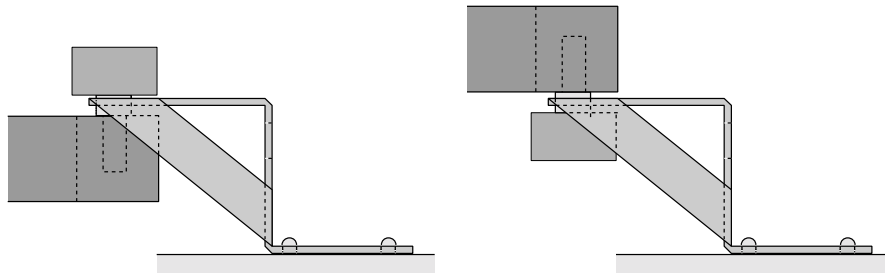
Profiles with unfixed end segments, however, had to be more carefully designed. For example, non-fixed segments should be as short and wide as possible to avoid deformation, as can be seen in Figure 3.9. Although some of these profiles could have been designed in a way that fixed both end segments, these considerations radically improved robustness.



*Figure 3.9: Robustness increased by careful design.*



Still, some profiles needed to be of significant length in order to reach connecting limbs. For these, robustness could not be improved by connecting the end segments with the height segments, since this would block limb rotation. This could have been solved by having the potentiometer connect to the limb above the profile, as shown in Figure 3.10, but doing so would increase the distance between the limb and the body. Thus, no such adjustments were made for these profiles.



*Figure 3.10: Blocked limb rotation vs. bad limb displacement.*

### **3.2.6. Supportive Pads**

Although the polyethane used for the supportive pads was easily shaped, the biggest challenge proved to be designing all different pads, since they would have to fit conveniently and not displace as the performer moved, nor interfere with body movement. Since the pads would be used where the exoskeleton would connect to the performer, they had to be tailored for each specific body part. Complete blueprints can be found in Appendix C.

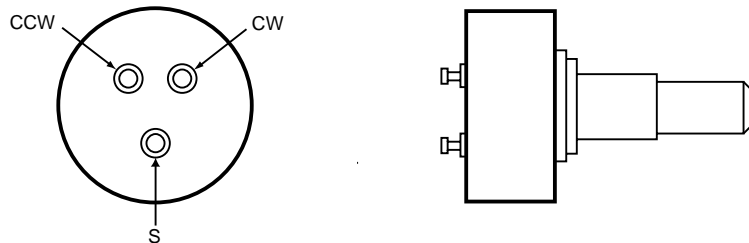
## **3.3. Electronics**

The practical design and implementation of the electronic circuits for this project has been made by Stefan Gustavson, and is in large parts identical to the electronics used for the Monkey prototype. What follows is a brief description of the electronics, circuitry and computer interface. Further details can be found on the Monkey project website [16] and Appendix A.

### **3.3.1. Potentiometers**

Potentiometers are variable resistors that vary the amount of current that flows through an electronic circuit. The ones used at the joints of the constructed exoskeleton are 10k $\Omega$ , high quality precision potentiometers from BI Technologies [17], model number 6187, shown in Figure 3.12. The potentiometers are of single turn type and have a free 360 $^\circ$  rotating axle with a specified lifetime expectancy of 5.000.000 turns. The components are

extremely robust, with an axle in durable bronze bearing and a sealed plastic cover. The cost for each potentiometer is approximately \$15, and considering the quality, price and robustness of these components, they are an ideal choice for this kind of application.



*Figure 3.11: Illustration of BI Technologies precision potentiometer, model 6187. The CW and CCW terminals connects to voltage and ground input respectively. The S terminal is signal output.*

### **3.3.2. Computer Interface**

The computer interface makes use of the standard PC parallel port, an old but reliable interface that is programmable on a very low level. Although it is an outdated interface that tends to disappear from modern standard PC's, the parallel port can be fully controlled down to individual bits with very high timing accuracy, thus making it a suitable interface for this project.

### **3.3.3. Circuitry**

In the electronic system, each individual channel is represented by a single potentiometer. To initiate the analog-to-digital (A/D) conversion of a channel, six address bits are sent from the parallel port data lines via the software, indicating which channel to be converted. The three last bits determine which of five multiplexers that is to be activated via a 3-to-8 decoder, while the first three bits indicate which specific channel of the multiplexer that is to be converted. The selected channel signal connects to the A/D converter via an operational amplifier, and a single control bit sent from the parallel port initiates the A/D conversion.

The A/D converter produces a 12-bit digital signal, which contains too many bits for the parallel port to handle. Therefore, the 12-bit digital data is divided into three 4-bit nybbles that are chosen using two 8-to-4 multiplexers addressed by two control bits. Once all three nybbles have been sent to the status lines, one status bit is sent to the computer indicating when the A/D conversion is done.

### 3.3.4. Wiring

Because of the large number of channels used in a full body system, there is need for serious consideration regarding the wiring of the system. Since each potentiometer requires separate cords for voltage and ground input as well as signal output, a large amount of cables has to be used. In order to reduce the wiring into a much more sparse and compact solution, the voltage and ground inputs to the potentiometers are connected in parallel.

To further reduce the wiring of the system, multi-conductor cables are used for signal output. Typically, the potentiometers are mounted in groups of two or three at each joint, therefore appropriate two- and three-conductor cables are used as signal cords. Small sockets are also attached to the end of the cords, making it easy to connect them to matching input pins on the circuit board.

The input cables are connected directly to the signal terminal of each potentiometer. However, to limit input voltage, the +10V and ground cables are connected to the CW and CCW terminals through small  $120\Omega$  resistors. Also, in order to prevent high frequency noise, a  $4.7\text{ nF}$  capacitor is placed between these terminals.

Figure 3.12 illustrates the circuitry at each potentiometer and the parallel connection of the voltage and ground input.

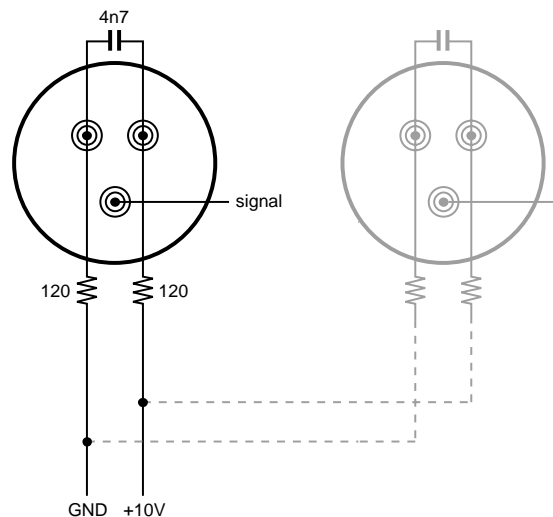


Figure 3.12: Illustration of resistor and capacitor placement at each potentiometer, with parallel connected voltage and ground inputs.

The use of small electronic circuits at each potentiometer is however not an ideal solution. The inevitable movement of the voltage and ground cables will lead to strain on the components, primarily the two resistors connected to the CW and CCW terminals. It is therefore important to make sure the legs of the resistors are sufficiently robust. Another solution is to connect the resistors to

the terminals via a sturdy cable, instead of soldering them directly onto the terminal pins.

## **3.4. Software**

This section describes the software developed for this project. First, a general overview of the system will be presented, followed by a brief description of the different software components and system specifications. Since the software implementation is relatively straightforward, details such as code fragments have been excluded from this report.

### **3.4.1. Overview**

In order to make the software solution as efficient and usable as possible, careful consideration was taken regarding the application structure. As mentioned in section 3.1, the decision to implement the software as a client-server solution was made early on. In addition to the already given reasons for this, it was also necessary from a system performance point of view. The amount of streaming data to the parallel port from an exoskeleton using up to 40 channels, would quickly make the system performance shoot up to 100%. Running an application with advanced OpenGL visualization and perhaps a data exporter on top of the hardware process would be extremely tough on the system. Thus, the idea of a server software dedicated to hardware sampling, data handling and further data distribution made a lot of sense. To make use of the actual Motion Capture data, for example real time visualization and data export, a separate software client running these processes would be needed.

The choice of protocol for distributing data between the server and client software was straightforward. The standardized TCP/IP protocol offers simple routines for sending and receiving data over the Internet [18]. Also, the use of the protocol is easily implemented using standard library routines in Linux or the Winsock library for Windows.

In choosing TCP/IP as the protocol to be used for this project, the idea of distributing real time Motion Capture data over long distances via the Internet was spawned, although the implementation of such functionality is not relevant to this specific project. The protocol implemented in the client-server solution for sending and receiving data across the TCP/IP network is adjusted for short distance communication. Hence, to prevent data loss, the server and client should preferably run within the same local network.

A schematic of the system data flow can be seen in Figure 3.13.

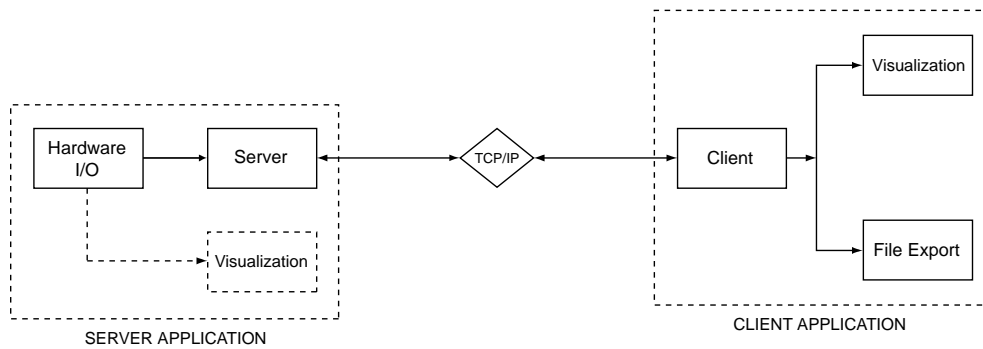


Figure 3.13: Data flow of the client-server solution.

### 3.4.2. Server Software

As mentioned earlier, the server software is dedicated to hardware sampling, data handling further data distribution. The program is module based in the sense that the different routines are separated, with hardware sampling done as a continuous process, only limited in speed by the clock frequency of the server computer.

The hardware interface receives the channel values in the form of a 12-bit integer (i.e. values between 0 and 4095) per channel, corresponding to the voltage produced by each potentiometer. To remove signal noise, each channel value is averaged over ten samples, and in order to translate these values into a more useable format, they are linearly scaled into a floating point Euler angle representation.

To increase performance, the server is implemented as a multithreaded application where the actual TCP/IP server is executed as a separate thread, continuously listening for incoming client connections. Once the clients connect to the server, data distribution for each client is run on a separate threaded loop that handles client requests and data transfer.

### 3.4.3. Calibration

Since the potentiometers provide absolute voltage output depending on their rotation, calibration of the system should not be needed. However, due to the fact that performers may not wear the Motion Capture suit in an identical manner from session to session, the initial signals from each potentiometer may differ. To prevent unreliable data due to this fact, a software-based calibration functionality has been implemented.

As the capture session begins, the performer takes a neutral upright pose. When the hardware sampling is initialized by the server, the signal for each potentiometer is zeroed by using the current voltage outputs as offset values.

Thus, the initial calibration pose will correspond to a  $0^\circ$  rotation for each joint, and all rotations thereafter will be relative to this orientation.

### 3.4.4. Client Software

Much like the server, the client software is a modular application that consists of several independent components. As seen in Figure 3.13, the application receives the Motion Capture data from the server via a TCP/IP client module. The data can be used by the system in a number of ways, such as real time visualization in OpenGL and data export.

When the client connects to the server, it initially receives configuration variables from the server, such as how many channels that are to be used for the current setup. Secondly, the client receives a hierarchical representation of the body structure of the performer. This representation holds information on limb offsets, limb names, rotation order and which channels that are to be used for X, Y, and Z-rotation of each limb, as seen in Figure 3.14. Hence, to make the system as general as possible, the client software receives all the information it needs from the server. This hierarchical representation is then used for both proper visualization and data export.

Name	Depth	Offset			Channel			Rot. Order
		X	Y	Z	X	Y	Z	
Hips	0	0.00	0.00	0.00	-1	-1	-1	XYZ
Chest	1	0.00	4.57	0.00	0	-1	1	ZXY
Chest2	2	0.00	8.81	0.00	3	4	2	YXZ
Neck	3	0.00	8.81	0.00	5	-1	6	XZY
Head	4	0.00	5.19	0.00	7	8	9	YXZ
End	5	0.00	7.14	0.00	-1	-1	-1	XYZ
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
LeftHip	1	3.43	0.00	0.00	24	27	25	XZY
LeftKnee	2	0.00	-18.47	0.00	26	-1	-1	XYZ
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.

*Figure 3.14: Example of hierarchical data initially sent from the server to the client, describing the skeletal setup of the current user. The Depth field indicates the relationship of the current node with respect to its parent. A value of -1 in one or more of the Channel fields indicates that the current joint has no rotation in the specific direction.*

Once the configuration has been received from the server, the client continuously requests data from the server at a given interval, for example 30 times per second. The data received from the server are standard floating point Euler angles for each limb and DOF.

### 3.4.5. BVH File Exporter

To make use of the actual Motion Capture data, a BVH-file exporter is integrated into the client software. The BVH file format [19] is a widely used Motion Capture file format supported by many commercial 3D software packages such as 3D Studio MAX [20] and Maya [21]. As opposed to several other file formats used for Motion Capture, the BVH format includes a hierarchy of the captured subject. The format is somewhat self explanatory, but will be explained briefly for clarity.

As can be seen in Appendix B, a BVH file is divided into two main sections. The top section, called the BVH header, describes the hierarchy and the initial pose of the skeleton that has been captured. Each node of the hierarchy, separated by curly braces, contains information on the joint name, order of rotation and its relative X-, Y- and Z offset to its parent, thus making the format a recursive definition of the captured subject. The *ROOT* node is defined to be the root joint of the skeleton, typically the hips of a human character, where three additional channels, *Xposition*, *Yposition* and *Zposition* corresponds to the character's absolute position in space. The *End Site* nodes represent the last chain in the link, where the offset values in practical are the lengths of the last limb.

The *MOTION* section of the BVH file contains the actual motion data, where each row of the data section represents one sample of motion data for every joint and DOF. Additional information, such as number of captured frames and sample interval, are defined prior to the actual data section.

As can be noticed in Figure 3.14, the hierarchical data sent from the server to the client has a striking resemblance to the BVH header information, with the addition of which channel that is to be used for each joint rotation.

### 3.4.6. Technical Specifications

As mentioned in Chapter 1, the software has been implemented using Open Source and free software and libraries. This decision was made not only because of budget restrictions, but also to allow further development under a non-commercial license. The programming language used is C/C++, compiled with GCC v. 3.0. Using GCC makes it easy to develop platform independent solutions, since it is available for both Linux and Windows platforms. For Linux, the software has been developed on a PC running Debian Linux, with its GCC compiler and editors such as Emacs. Windows development makes use of Dev-C++ [22], an IDE for Win32 development with its accompanying GCC compiler. Graphics libraries used are OpenGL with GLUT for Windows and glut3 for Linux. GUI components have been implemented using the Open Source GUI library FOX Toolkit [23].

To make future development easier and to keep the system modular, it has been developed using object oriented programming concepts.

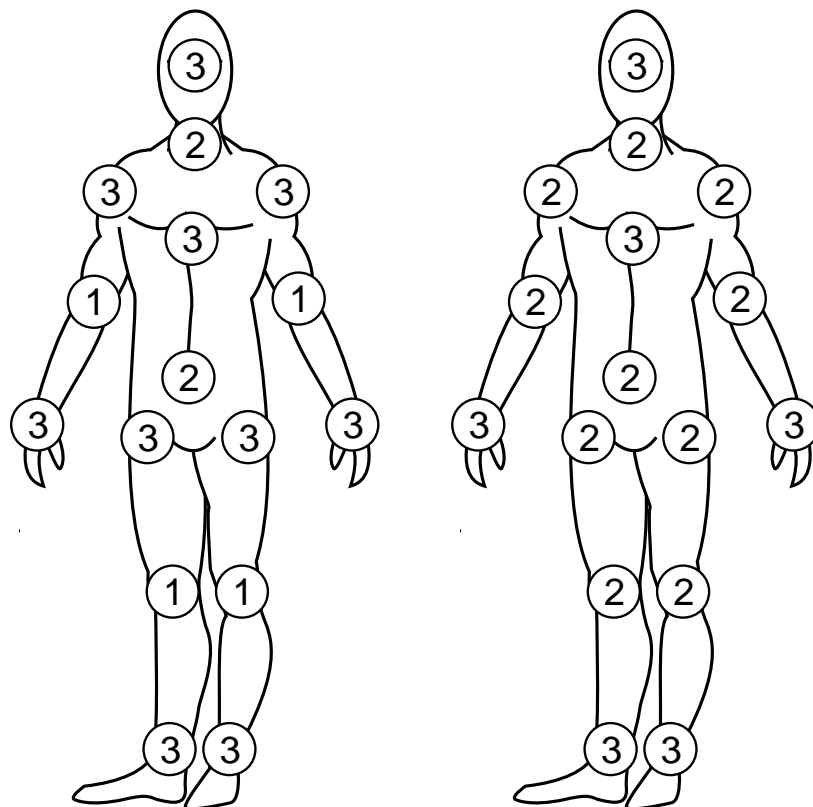
## 4. Results

This chapter will discuss the outcome of this diploma work, presenting results for the different process components.

### 4.1. Mechanics

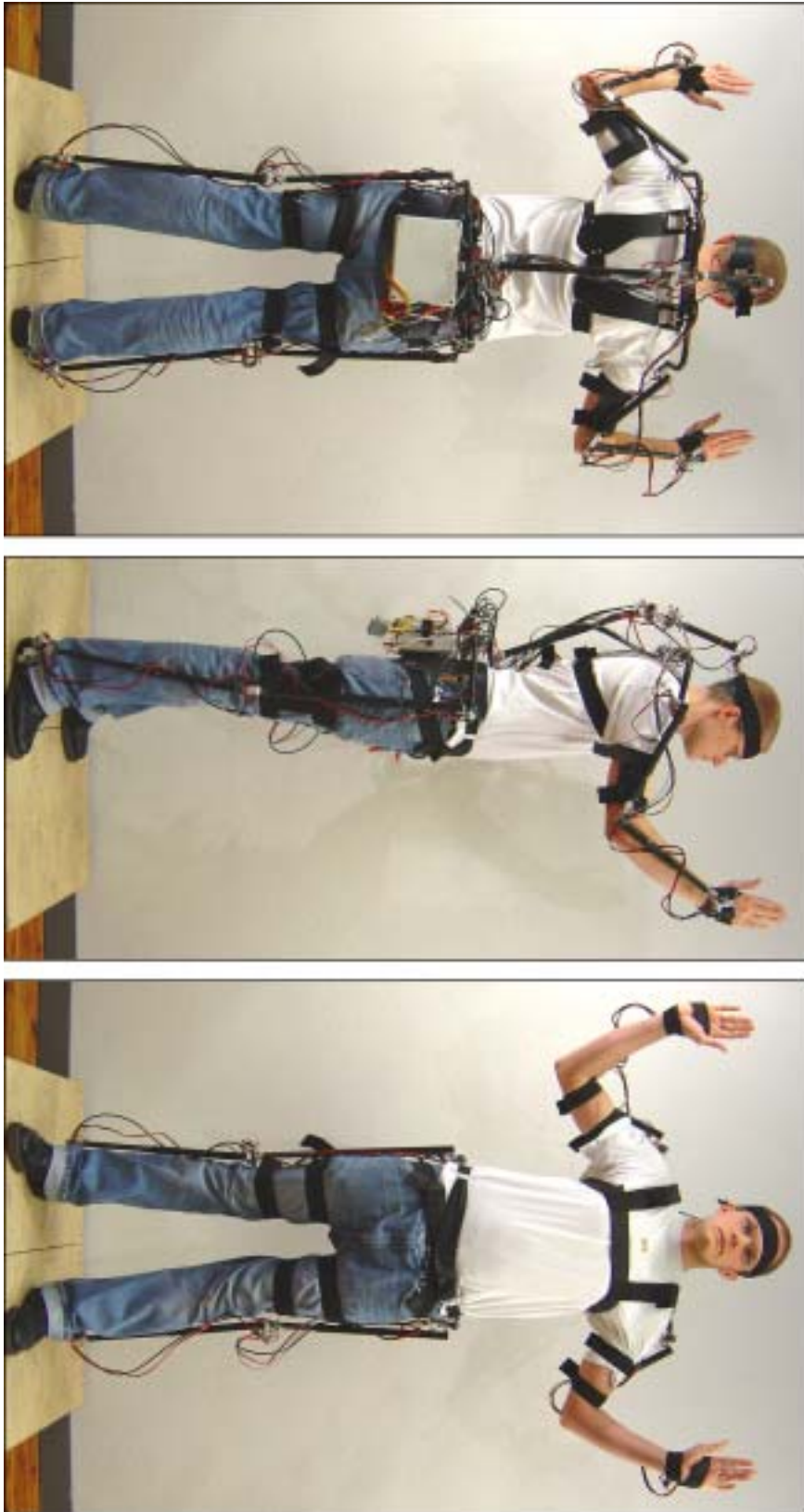
The mechanical outcome of this diploma work is a full body exoskeleton that is constructed of lightweight materials and allows for 38 unique rotations at 16 joints. The suit is easily constructed using basic tools and the blueprints found in Appendix C, and can be done so at a very low cost. Pictures of the exoskeleton being worn by a performer can be seen in Figure 4.2

Beginning with designing and constructing a prototype exoskeleton for the entire left side of the body, major flaws in the initial design have been adjusted in the final construction. For example, the initial potentiometer setup has been modified to avoid Gimbal Lock and provide better rotational response, as shown in Figure 4.1.

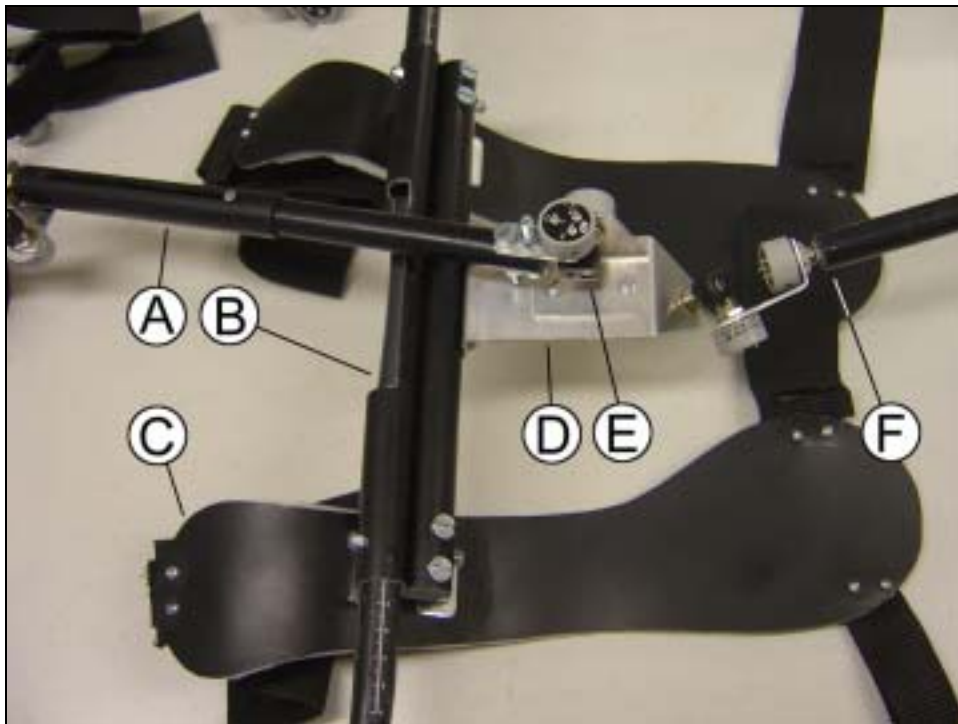


*Figure 4.1: While the initial potentiometer setup, shown to the left, corresponds to the joint characteristics of a human body, the rightmost has been configured to avoid Gimbal Lock and provide better rotational response. The numbers indicate the DOF at each joint.*





*Figure 4.2: Performer wearing the full body exoskeleton..*



*Figure 4.3: Exoskeleton parts.*

*A) Limb B) Supportive bar C) Supportive pad D) Profile E) Block F) Plug*

Figure 4.3 shows all part types of the exoskeleton. The telescope limbs are constructed with two layers of pipes that smoothly expand and contract as the performer moves. The limbs are either fully or partially locked by the single- or double-slit solutions proposed in section 3.2.3, and allow unrestricted movement for most limbs.

The blocks and plugs are carved out of PVC-C bars and hold the potentiometers in place by bolts screwed into the plastic. The blocks are small to support free rotation inside the joints, and each plug is shaped to fit the inner radius of its corresponding pipe.

Many different profiles have been used for the exoskeleton, all made of soft aluminum. They are either attached to supporting pads by fits rivets or to plastic bars by bolts, and are at most joints robust enough to not bend during movement.

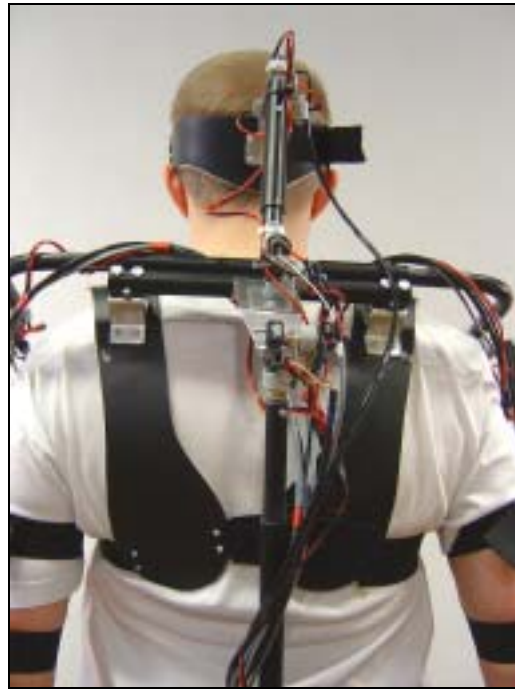
The supportive pads are made of polyethane and inwardly coated with a layer of foam rubber that protects the user from any sharp edges or fits rivets. The pads are fastened to the body by elastic bands that are fixed by Velcro®, either directly to the pad or to the elastic band itself. This makes the pads firm as well as flexible once fixed. The rear pads, for example, have been designed to be both robust and comfortable to wear, and are firmly attached to the body by elastic bands crossed over the stomach.

Furthermore, the spine limb has been divided into four joints in order to account for internal movements and rotations. A close-up of the three upper joints can be seen in Figure 4.4. The back is fixed to the body by one band tightened over the chest and two coming down from the shoulders, and the shoulder pads can be adjusted by a band as well.

As the neck has no noticeable internal rotation in spine direction, 2DOF were sufficient. The head joint can be fully rotated and is connected to the back of the head via a large pad that is tightened around the forehead, as previously described. The result is shown in Figure 4.5.

Being the most flexible joints, the shoulders have been designed to avoid Gimbal Lock. Thus, the profiles have been diminished and the setup modified as can be seen in Figure 4.1, with the y-rotation moved to the elbow.

Since the hips are much more restricted in movement than the shoulders, the 3DOF could have been preserved as in the original design. Still, as the updated setup was proven to work well, while also being far simpler to construct, the legs have been designed in the same way as the arms, moving the y-rotation to the knee joint. Furthermore, the lower body can be easily disconnected by removing two bolts, which makes it easy to adjust the system to only capture upper body motion data.



*Figure 4.4: The three upper spine joints - upper chest, neck and head.*



*Figure 4.5: Close-up of the head and neck joints.*



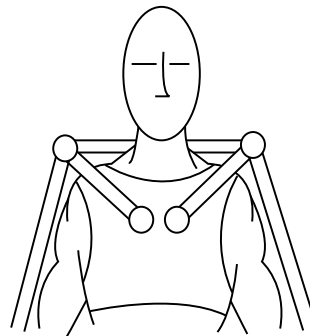
*Figure 4.6: Close-up of the arm*



*Figure 4.7: Close-up of the leg*

While working with the shoulders, the collar bones were found to be a bigger problem than first assumed. To track their movement, the potentiometers in question would have to be fixed to the body, for example as shown in Figure 4.8. If not connected to the body, the collar bones would move relative to the shoulders and the back, giving an erroneous result.

Since this problem occurred late in the project, the design and construction of a solution like the one in Figure 4.8 would have required a major redesign of the exoskeleton. The collar bones were thus disregarded for the final exoskeleton, making the final system unable to trace movements like shrugs.

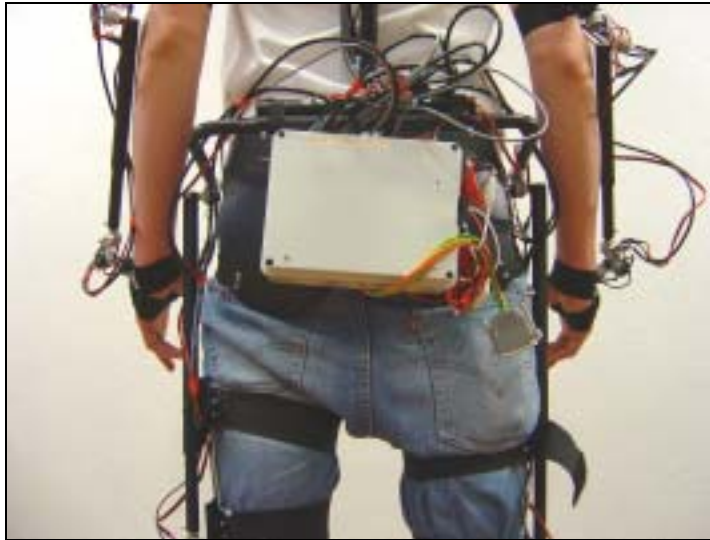


*Figure 4.8: Illustration of possible collar bone solution.*

## **4.2. Electronics**

While the original electronic circuit for the Monkey prototype only supported eight channels using one analog multiplexer, the circuit has been expanded to make use of five multiplexers, thus supporting up to 40 channels. To make place for all supported channels, all multiplexers and channel inputs are placed on a separate circuit, bridging them to the original circuit board.

Power for the circuit and potentiometers can be supplied either from a portable 9V battery pack or an external 220V outlet. Both circuit boards are mounted inside a plastic case that is attached to the rear end pads to maximize portability, as can be seen in Figure 4.9. By doing this, only the parallel cord connecting the electronic circuit to the PC and the voltage supply (if not using the battery pack) are required to spring from the performer.



*Figure 4.9: Electronic unit attached to the rear pads.*

### **4.3. Software**

The implemented software provides a stable client-server solution that makes use of the TCP/IP protocol for data distribution. Multiple clients can successfully connect to the server, receive motion data in real time and use the data appropriately. What follows is a brief description of the server and client features respectively.

#### **4.3.1. Server Software**

For simple access to parallel port routines, the server application is developed under Linux and should run on any POSIX-based system. Due to the need for parallel port access, the program must also be run by a user with administrative privileges. Making the server software run under a Windows environment would require system dependent hardware routines to be implemented.

The graphical user interface for the server, shown in Figure 4.10, lets the user configure the server in a number of ways. First of all, the user has the option to choose if a full body or just an upper body is to be tracked. The hardware interface will sample the appropriate channels for the current configuration, and the TCP/IP server will only distribute data for these channels to connecting clients. Furthermore, the user has the option to choose on which port the TCP/IP server will run, as well as how many incoming client connections should be allowed.

If the system performance allows it, the user can turn on a simple OpenGL visualization to get instant visual feedback of the data that is sampled and sent to the clients. Activating the visualization in the server software will however

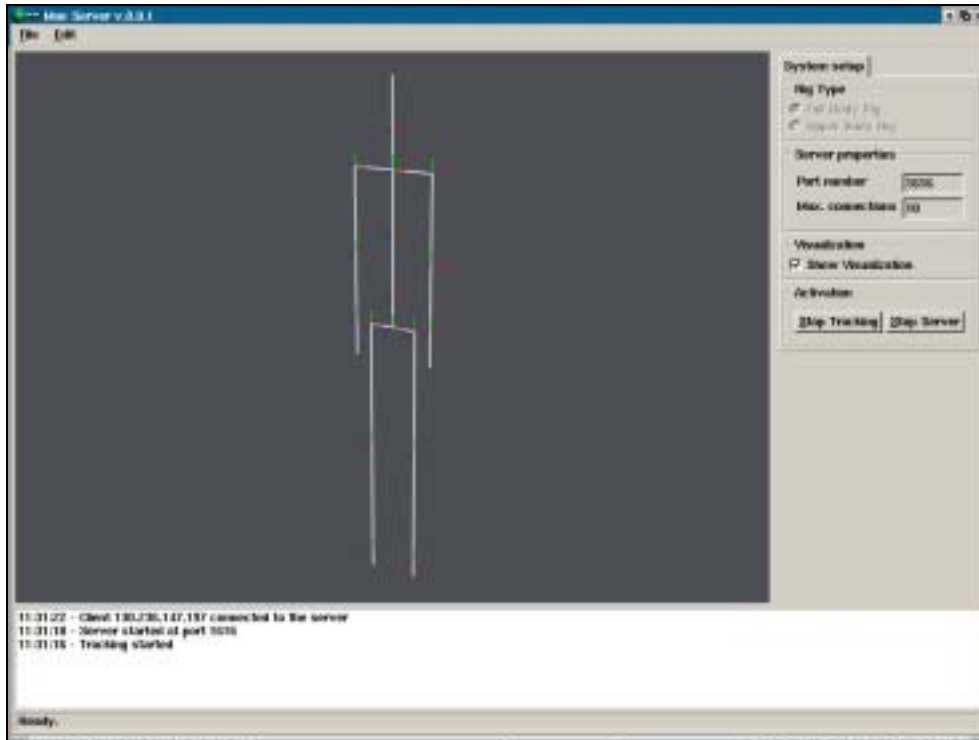


Figure 4.10: Server software GUI.

seriously reduce system performance, and is therefore not recommended. Finally, the user is able to start or stop the hardware sampling and the TCP/IP server at any time, using the two buttons in the bottom right corner. All server activities, such as incoming connections, hardware initialization etc., are printed in a server log placed at the bottom left corner of the user interface.

Performance-wise, with the server software running on a Pentium II, 350 MHz PC, a hardware sampling rate of 45 kHz has been recorded. This allows for 40 channels to be sampled more than 1000 times per second, which is more than sufficient for this purpose.

#### 4.3.2. Client Software

The major part of the client user interface is devoted to OpenGL visualization to give the user clear visual feedback of the Motion Capture data, as shown in Figure 4.11. Apart from that, the user can choose which server to connect to by entering the IP address and port number of the running server.

Furthermore, the GUI also allows for the user to choose in which mode the visualization is to be rendered, such as wireframe or solid mode. The bottom right part of the interface is devoted to file export controls, where the user can choose when to start and stop the recording of motion data.

The client software compiles both under Windows and Linux and should therefore run on most computers.

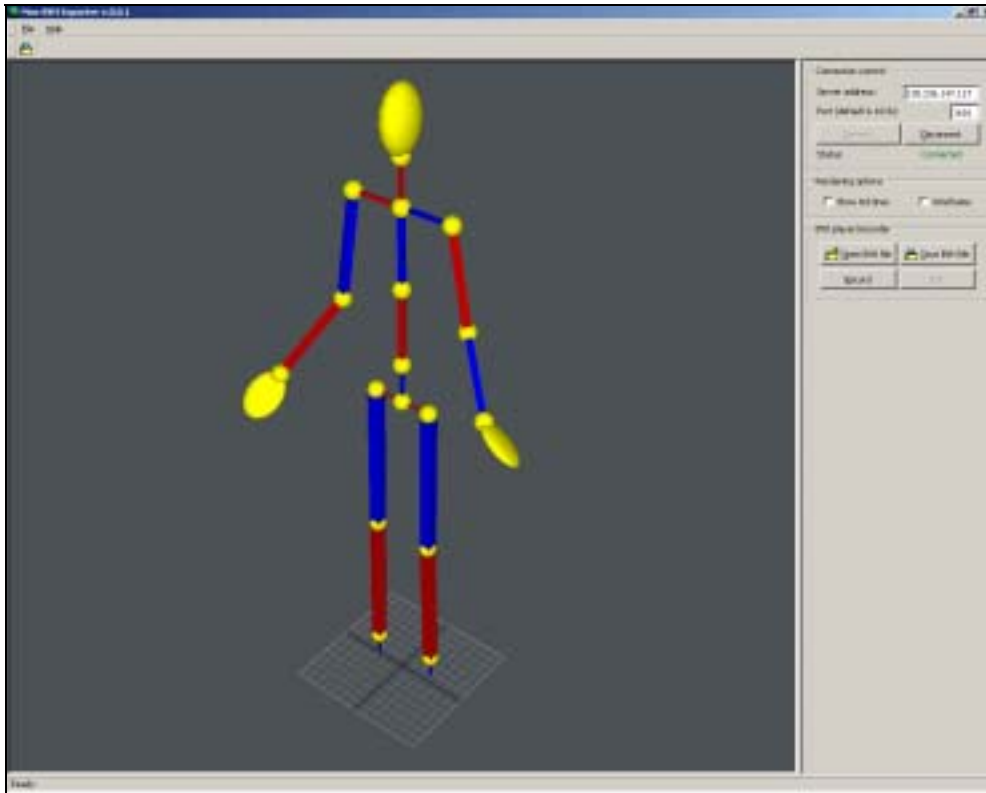


Figure 4.11: Client software GUI.

#### 4.4. Capture Examples

Figure 4.12 features images from a capture process, where a *live performance* is being visualized in *real time* on a client that is running the BVH file exporter. The BVH file is then imported into 3D Studio Max and mapped on a *Biped*, and the Biped is then finally *rendered* with a high-resolution model on top.



*Figure 4.12: Live performance, real time visualization, 3D Studio Max Biped and 3D Studio Max render.*

As may be noticed, the software results differ slightly from the true movement of the performer. This is due to the fact that the obtained angles correspond to the behavior of the exoskeleton instead of the internal skeletal movement of the performer. In order to account for this, algorithms to trace correct limb rotations must be implemented.

The importance of careful calibration can be seen at the hands, which are slightly rotated out from the body. Correct rotation of the hands during the calibration would have given a better result.

Below are samples from two different capture processes. Frames from live performances are shown with corresponding final renders below.







## 4.5. Hardware Cost

The table to the right lists approximate costs for the hardware and materials used to construct the exoskeleton, as well as the electronic circuits. As can be seen, the major hardware cost for the entire system lies in the high quality potentiometers used by the exoskeleton. In general, the electronic components used stand for most of the budget, where materials for mechanics and textiles are very inexpensive.

<b>Mechanics</b>	<b>USD</b>
Polyethane plastic	\$9
PVC-C piping & bars	\$13
Aluminium	\$11
Fits rivets	\$4
Tangit glue	\$9
Various bolts & nuts	\$18
Metal rings	\$3
<b>Textiles</b>	
Rubber foam	\$6
Velcro	\$18
Elastic bands	\$29
Plastic harness	\$5
<b>Electronics</b>	
Potentiometers	\$527
Resistors	\$25
Capacitors	\$11
Voltage & ground cable	\$6
Signal cables	\$107
Circuit boards	\$33
A/D converter	\$38
Multiplexers	\$12
Buffers, decoders, amplifier	\$14
Plastic case	\$6
Parallel port socket	\$9
Other	\$36
<b>Total</b>	<b>\$949</b>

## 5. Discussion

This chapter will discuss the outcome of this diploma work and suggest some further work and developments that can be made to improve the system.

### 5.1. Conclusions

This thesis presents a high quality real time Motion Capture system developed with strictly limited resources. The system proposed is fairly robust and makes use of cheap materials and components, thus allowing for smaller studios or other technical institutions to implement their own Motion Capture system instead of purchasing an expensive commercial alternative.

The constructed exoskeleton is a reasonably light suit that is easy to put on and take off, although the use of more professional and durable materials could have allowed for a better design. The most flexible joints are still quite limited in movement and may suffer from Gimbal Lock if the exoskeleton is not carefully adjusted when being attached to the performer.

The motion data obtained from the exoskeleton is generally noise-free and of high quality, and the 12-bit data resolution allows for even subtle movements to be properly tracked. Still, being an exoskeletal approach, the motion data received from some joints is not entirely accurate due to the fact that the exoskeletal motion does not correspond to the actual internal skeletal movements of the performer. This problem is most apparent for the joints between the pelvis and the head.

Looking at the software, the TCP/IP approach works well provided that both server and clients are working on a fast Internet connection. Still, since slow connections conflict with the real time aspect, this is not considered to be an issue. Furthermore, the way of having several clients connect to the server and accessing motion data separately has proven to work well, providing a very flexible and expandable system.

In conclusion, although several improvements can be made regarding both mechanics and software, the implemented system meets both the initial objectives and budget requirements, with a total cost of approximately \$950.

### 5.2. Future Work

*Materials.* Since the PVC-C is easily torn, several suggestions that would increase joint flexibility and decrease the risk of Gimbal Lock had to be disregarded. Effort should be put into finding a more durable material that still meets the initial mechanical requirements.

*Telescope flexibility.* The telescopic limbs should consist of more than two pipe layers. This would increase limb flexibility and provide a solution that would fit a wider range of body types.

*Collar bones.* Although the collar bones were disregarded due to lack of time, such a solution could quite easily be constructed as described in section 4.1, and would make it possible to track movements such as shrugs.

*Absolute position.* A big limitation with the current system is its inability to track absolute position and orientation. This could be obtained by using accelerometers or gyros, although these techniques are quite expensive. Still, if economic resources are available, such an enhancement should be among the first to be made.

*Electronics.* To further increase portability and comfort, the electronic circuit could be reduced into a more compact solution, with all components placed on a professionally made circuit board. Also, instead of using the outdated parallel port, a more modern interface such as USB would allow for higher data rates and future compatibility with modern PC's. Using such an interface would make it possible to run the server on a small portable PC, for example a PocketPC. In combination with a wireless network connection, such a solution would dramatically increase system portability.

*Data handling.* To obtain data that accurately represents the true movement of the performer, a comprehensive software-based data handler would be needed to calculate the internal skeletal movements based on the exoskeletal data.

*Protocol.* The transfer protocol implemented for motion data distribution over the TCP/IP network can be greatly improved. This would increase system performance when communicating over longer distances, since the current protocol does not handle loss of data.

*File export.* Even though the BVH format is the most commonly used Motion Capture file format, the client software could be expanded to include data export support for other formats, such as BVA, ASF and CSM files.

### **5.3. Applications**

Apart from the current real time visualization and file export functionalities, the system could be used in several ways. Below is a couple of possible applications that could make use of the motion data.

*Virtual Mirror.* By running a powerful real time visualization on a nearby computer, the system could be used as a virtual mirror, reflecting every movement of the performer. Areas of use could be to visualize new clothing designs, haircuts etc. These applications would need separate implementation of algorithms such as cloth, skin and hair simulations.

*Gaming interface.* Instead of traditional game interfaces such as joysticks, mouse and keyboard, the system could be used as a full body interaction system. Using real movement for interaction, such as walking, opening doors by hand movement and so on, immersion could be dramatically increased. Furthermore, the TCP/IP approach would make it possible to have several performers in the same environment, for example a two player boxing fight or a dramatic chess game. Other possible applications could be interactive entertainment, for example virtual tennis, golf or drumming, where user interaction plays a central role.

*Full body tool.* The gaming interface suggestion could be generalized into using the system as an interface for several different applications and environments, such as a CAVE or a VR workbench like the Vortex system used at Norrköping Visualization and Interaction Studio (NVIS) [24]. Such systems often allows for absolute positioning, and using these features in combination with the implemented motion capture system could produce a powerful interaction tool to be used to navigate and interact within a virtual environment.

*Virtual presenter.* Instead of visualizing the motion data as being done in the current system, it could be used for live performance in a more advanced context, such as a large-scale virtual environment. For example, a VR theater like the one being used at NVIS could make use of motion capture data to drive the movements of a virtual presenter for live shows. The host of the show would wear the motion capture suit during the presentation, continuously displaying a virtual avatar of him/her on the screen, thus introducing an interesting element of host/audience interaction.

## 6. References

### 6.1. Books

- [1] Menache, A., 2002, *Understanding Motion Capture for Computer Animation and Video Games*, Morgan Kaufmann, ISBN 0-12-490630-3

### 6.2. Articles & Papers

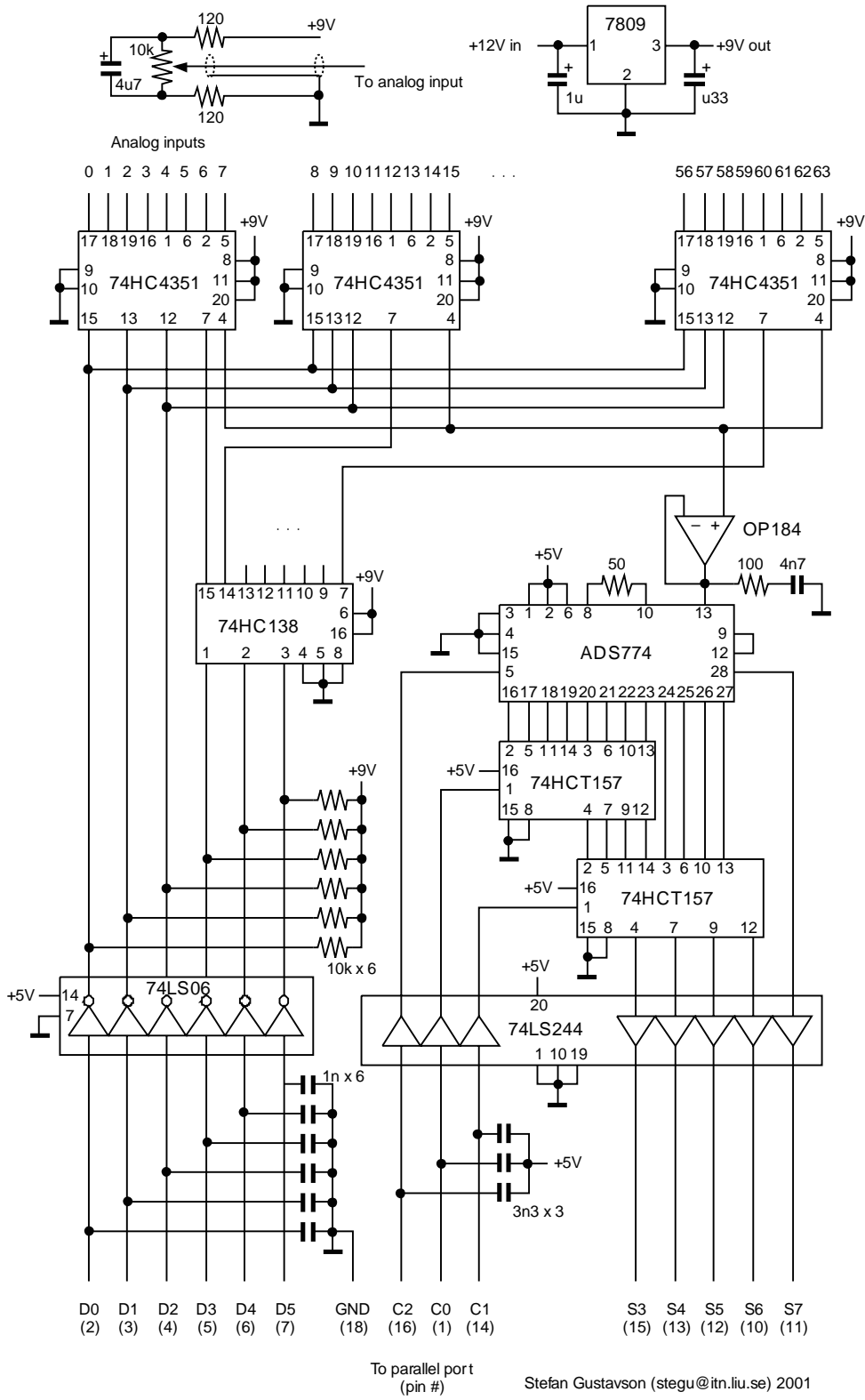
- [2] Carranza, J., Theobalt, C., Magnor, M.A., Seidel, H-P., 2003, *Free-Viewpoint Video of Human Actors*, MPI Informatik, Saarbrücken, Germany
- [3] Gustavson, S., 2002, *Motion Capture Done Dirt Cheap*, ITN Linköping Institute of Technology
- [4] Gustavson, S., 2002, "High quality, low cost real time motion capture unit for a PC (some assembly required)", ITN Linköping Institute of Technology

### 6.3. Internet

- [5] Meta Motion Website, <http://www.metamotion.com>, 2005-02-21
- [6] Motion Analysis Corporation Website, <http://www.motionanalysis.com>, 2005-02-21
- [7] Vicon Motion Systems Ltd. Website, <http://www.vicon.com>, 2005-02-21
- [8] Qualisys Website, <http://www.qualisys.se>, 2005-02-21
- [9] Scill Technologies Inc. Website, <http://www.skilltechnologies.com>, 2005-02-21
- [10] Polhemus Website, <http://www.polhemus.com>, 2005-02-21
- [11] noDNA Website, <http://www.nodna.com>, 2005-02-21
- [12] InterSense Website, <http://www.isense.com>, 2005-02-21
- [13] O-Navi Website, <http://www.o-navi.com>, 2005-02-21
- [14] Digital Image Design Inc. Website, <http://www.didi.com>, 2005-02-21

- [15] Sketches & Applications SIGGRAPH 2002 Website  
<http://www.siggraph.org/s2002/conference/sketches/03.html>,  
2005-02-21
- [16] Monkey Project Website, <http://www.itn.liu.se/~stegu/monkey/>,  
2005-02-21
- [17] BI Technologies Website, <http://www.bitechnologies.com>, 2005-02-21
- [18] Beej's Guide to Network Programming,  
<http://www.ecst.csuchico.edu/~beej/guide/net/>, 2005-02-21
- [19] Biovison BVH Website, <http://www.cs.wisc.edu/graphics/Courses/cs-838-1999/Jeff/BVH.html>, 2005-02-21
- [20] Discreet Website, <http://www.discreet.com>, 2005-02-21
- [21] Alias Website, <http://www.alias.com>, 2005-02-21
- [22] Bloodshed Software Website, <http://www.bloodshed.net>, 2005-02-21
- [23] FOX Toolkit Website, <http://www.fox-toolkit.org>, 2005-02-21
- [24] NVIS Website, <http://nvis.itn.liu.se>, 2005-02-23

# 7. Appendix A - Electronic Schematics



## 8. Appendix B - BVH Example File

```

HIERARCHY
ROOT Hips
{
  OFFSET 0 0 0
  CHANNELS 6 Xposition Yposition Zposition Zrotation Xrotation Yrotation
  JOINT Chest
  {
    OFFSET 0.000000 4.570000 0.000000
    CHANNELS 3 Zrotation Xrotation Yrotation
    JOINT Chest2
    {
      OFFSET 0.000000 8.810000 0.000000
      CHANNELS 3 Zrotation Xrotation Yrotation
      JOINT Neck
      {
        OFFSET 0.000000 8.810000 0.000000
        CHANNELS 3 Zrotation Xrotation Yrotation
        JOINT Head
        {
          OFFSET 0.000000 5.190000 0.000000
          CHANNELS 3 Zrotation Xrotation Yrotation
          End Site
          {
            OFFSET 0.000000 7.140000 0.000000
          }
        }
      }
      JOINT LeftCollar
      {
        OFFSET 0.000000 0.000000 0.000000
        CHANNELS 3 Zrotation Xrotation Yrotation
        JOINT LeftShoulder
        {
          OFFSET 5.810000 0.000000 0.000000
          CHANNELS 3 Zrotation Xrotation Yrotation
          JOINT LeftElbow
          {
            OFFSET 0.000000 -12.080000 0.000000
            CHANNELS 3 Zrotation Xrotation Yrotation
            JOINT LeftWrist
            {
              OFFSET 0.000000 -9.820000 0.000000
              CHANNELS 3 Zrotation Xrotation Yrotation
              End Site
              {
                OFFSET 0.000000 -5.370000 0.000000
              }
            }
          }
        }
      }
      JOINT RightCollar
      {
        OFFSET 0.000000 0.000000 0.000000
        CHANNELS 3 Zrotation Xrotation Yrotation
        JOINT RightShoulder
        {
          OFFSET -5.810000 0.000000 0.000000
          CHANNELS 3 Zrotation Xrotation Yrotation
          JOINT RightElbow
          {
            OFFSET 0.000000 -12.080000 0.000000
            CHANNELS 3 Zrotation Xrotation Yrotation
            JOINT RightWrist
            {
              OFFSET 0.000000 -9.820000 0.000000
              CHANNELS 3 Zrotation Xrotation Yrotation
              End Site
              {
                OFFSET 0.000000 -5.370000 0.000000
              }
            }
          }
        }
      }
    }
  }
}
JOINT LeftHip
{
  OFFSET 3.430000 0.000000 0.000000
  CHANNELS 3 Zrotation Xrotation Yrotation
  JOINT LeftKnee
  {
    OFFSET 0.000000 -18.469999 0.000000
    CHANNELS 3 Zrotation Xrotation Yrotation
    JOINT LeftAnkle
    {
      OFFSET 0.000000 -17.950001 0.000000
    }
  }
}
}

```



```

CHANNELS 3 Zrotation Xrotation Yrotation
End Site
{
    OFFSET 0.000000 -3.120000 0.000000
}
}
}
JOINT RightHip
{
    OFFSET -3.430000 0.000000 0.000000
    CHANNELS 3 Zrotation Xrotation Yrotation
    JOINT RightKnee
    {
        OFFSET 0.000000 -18.469999 0.000000
        CHANNELS 3 Zrotation Xrotation Yrotation
        JOINT RightAnkle
        {
            OFFSET 0.000000 -17.950001 0.000000
            CHANNELS 3 Zrotation Xrotation Yrotation
            End Site
            {
                OFFSET 0.000000 -3.120000 0.000000
            }
        }
    }
}
}
}
MOTION
Frames: 393
Frame Time: 0.040000
0.00 0.00 0.00 0.00 0.00 0.00 -0.28 -2.42 0.00 3.20 1.47 -1.49 -4.14 2.43 0.00 ...
0.00 0.00 0.00 0.00 0.00 0.00 0.10 -3.07 0.00 3.74 3.28 -0.61 -4.65 1.39 0.00 ...
0.00 0.00 0.00 0.00 0.00 0.00 -0.10 -3.48 0.00 3.98 2.36 -0.62 -4.39 3.40 0.00 ...
0.00 0.00 0.00 0.00 0.00 0.00 0.30 -2.09 0.00 3.49 0.76 -0.61 -3.93 3.95 0.00 ...
0.00 0.00 0.00 0.00 0.00 0.00 0.69 -1.80 0.00 3.43 2.27 -0.51 -4.32 2.65 0.00 ...
0.00 0.00 0.00 0.00 0.00 0.00 0.60 -2.83 0.00 4.18 3.12 -0.46 -4.60 3.51 0.00 ...
0.00 0.00 0.00 0.00 0.00 0.00 0.83 -2.68 0.00 3.89 1.43 -0.51 -4.10 5.16 0.00 ...
0.00 0.00 0.00 0.00 0.00 0.00 1.60 -1.94 0.00 3.89 0.94 -0.46 -3.66 4.38 0.00 ...
0.00 0.00 0.00 0.00 0.00 0.00 1.99 -2.23 0.00 4.27 0.85 -0.47 -3.45 3.11 0.00 ...
.
.
.

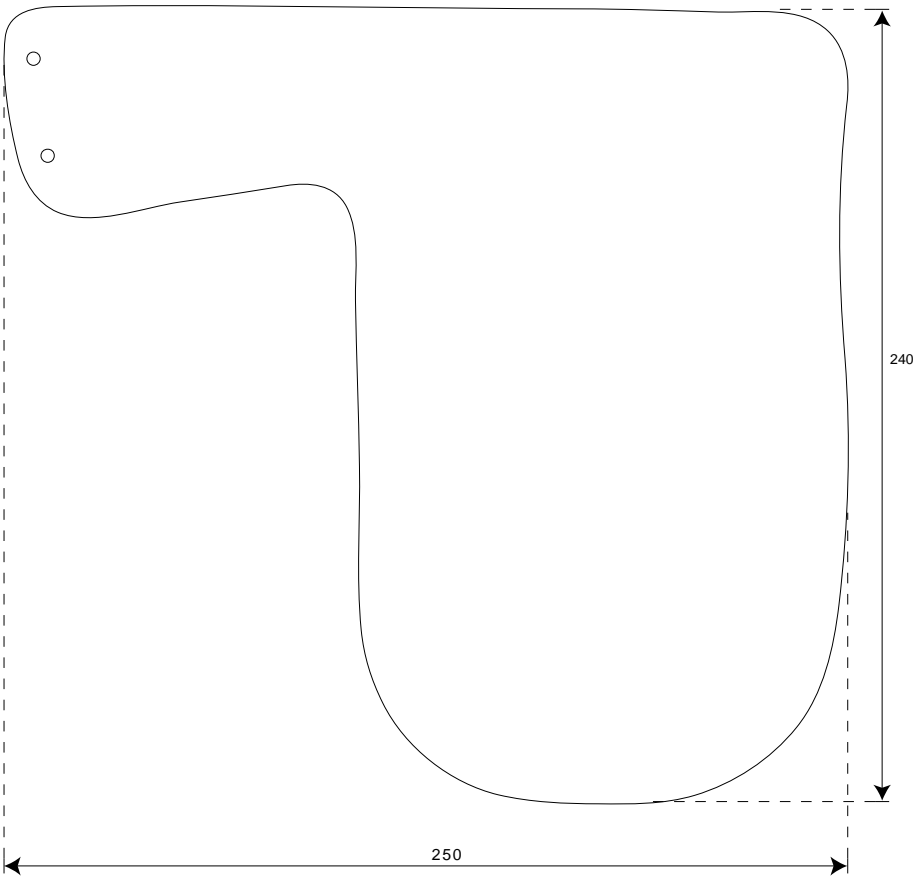
```

## **9. Appendix C - Mechanical Blueprints**

On the following pages, complete blueprints of all different parts of the exoskeleton will be listed in the same order as being described in section 3.2.

Name: Rear Pad

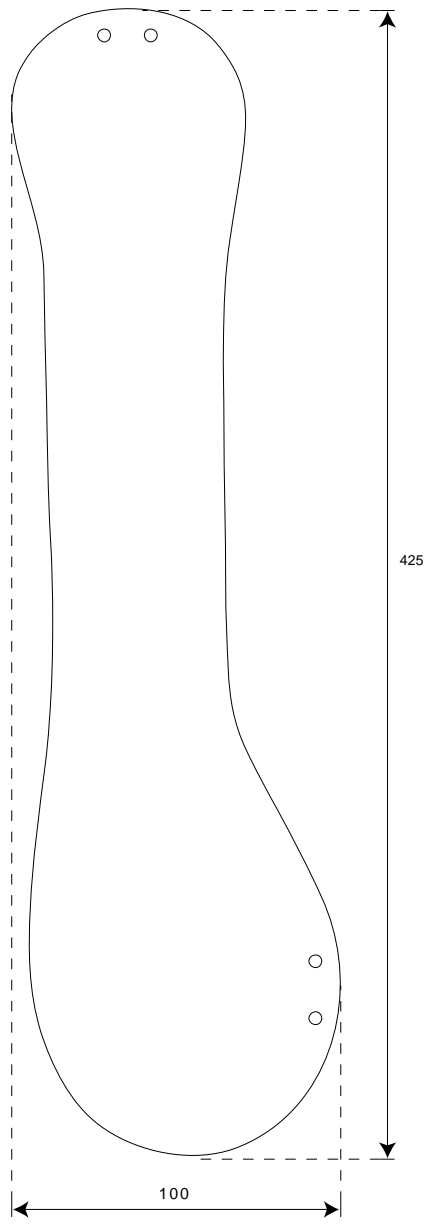
Quantity: 2



Unit: mm

Name: Shoulder Pad

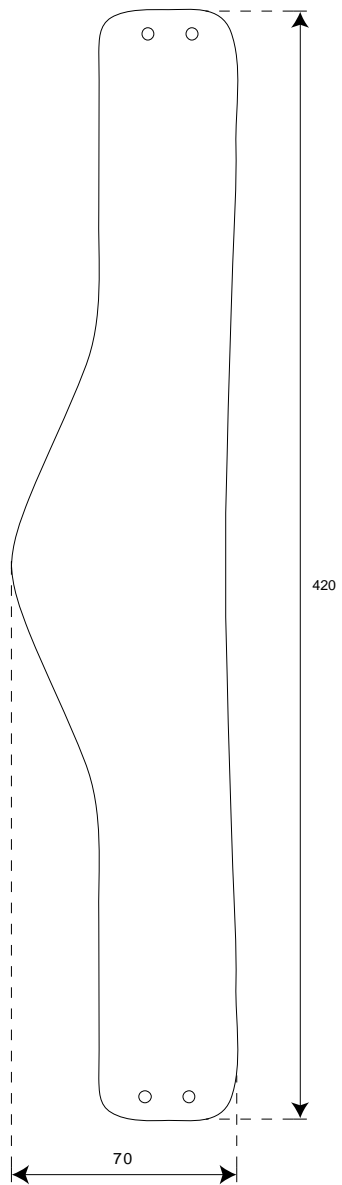
Quantity: 2



Unit: mm

Name: Head Pad

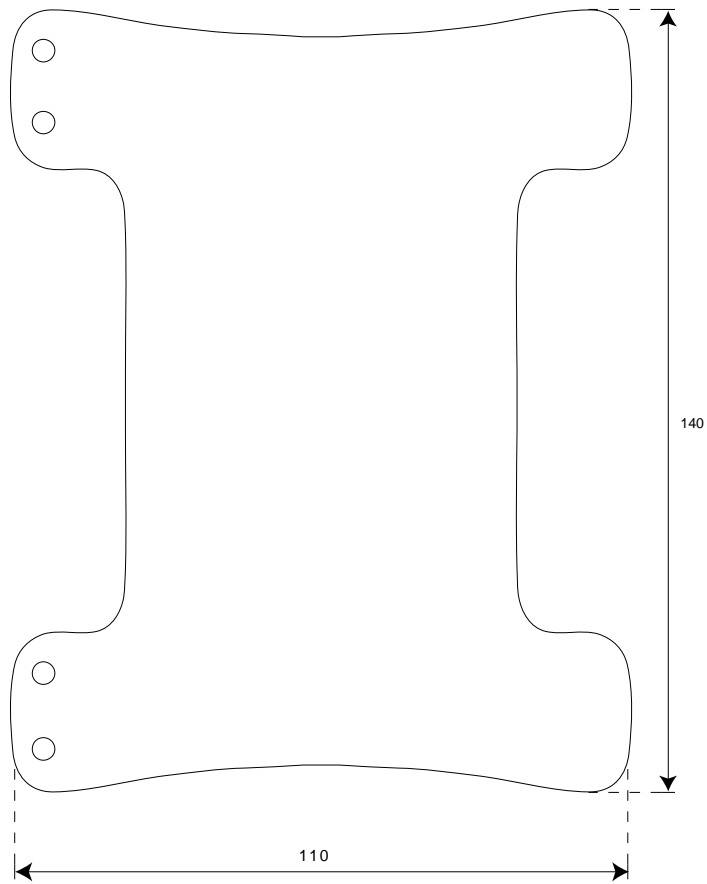
Quantity: 1



Unit: mm

Name: Arm Pad

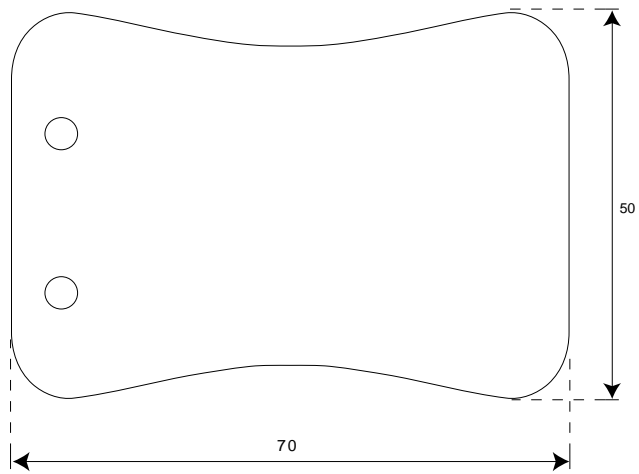
Quantity: 2



Unit: mm

Name: Hand Pad

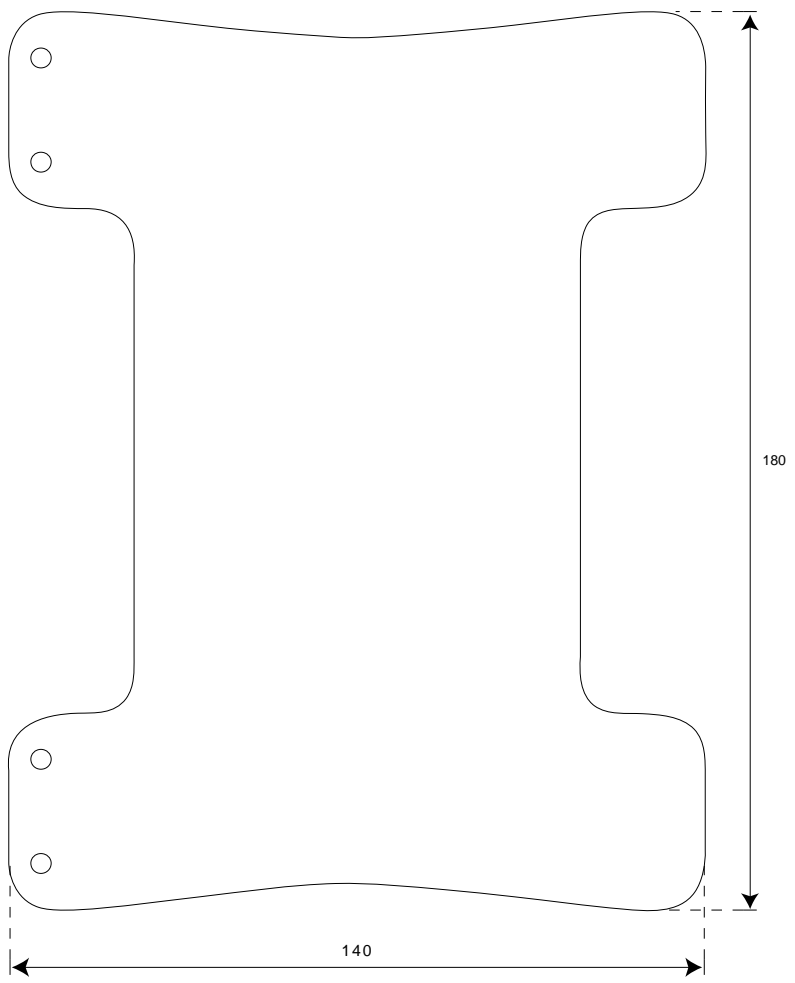
Quantity: 2



Unit: mm

Name: Leg Pad

Quantity: 2

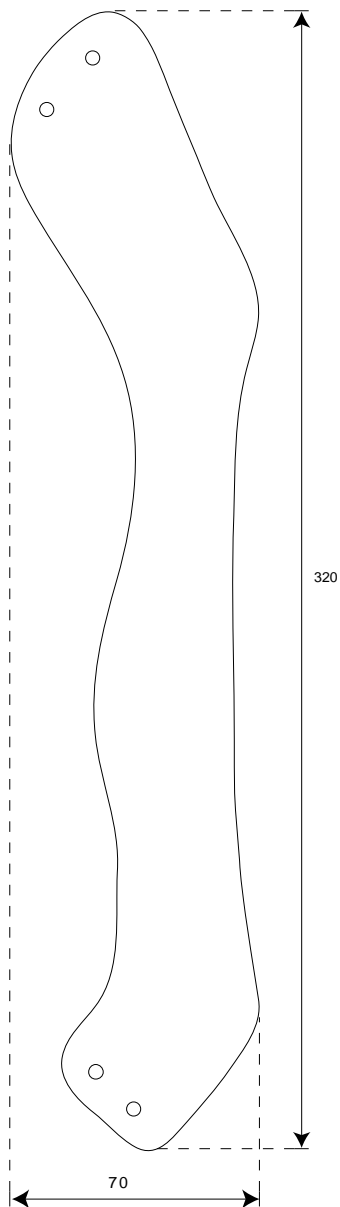


Unit: mm



Name: Foot Pad

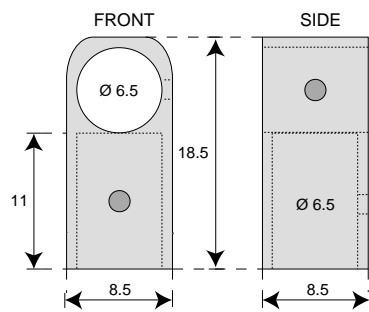
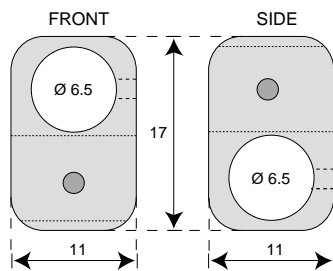
Quantity: 2



Unit: mm

Names: Block 1, Block 2

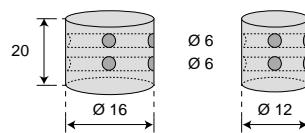
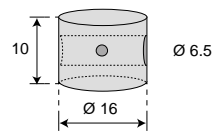
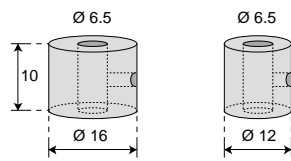
Quantities: 7, 1



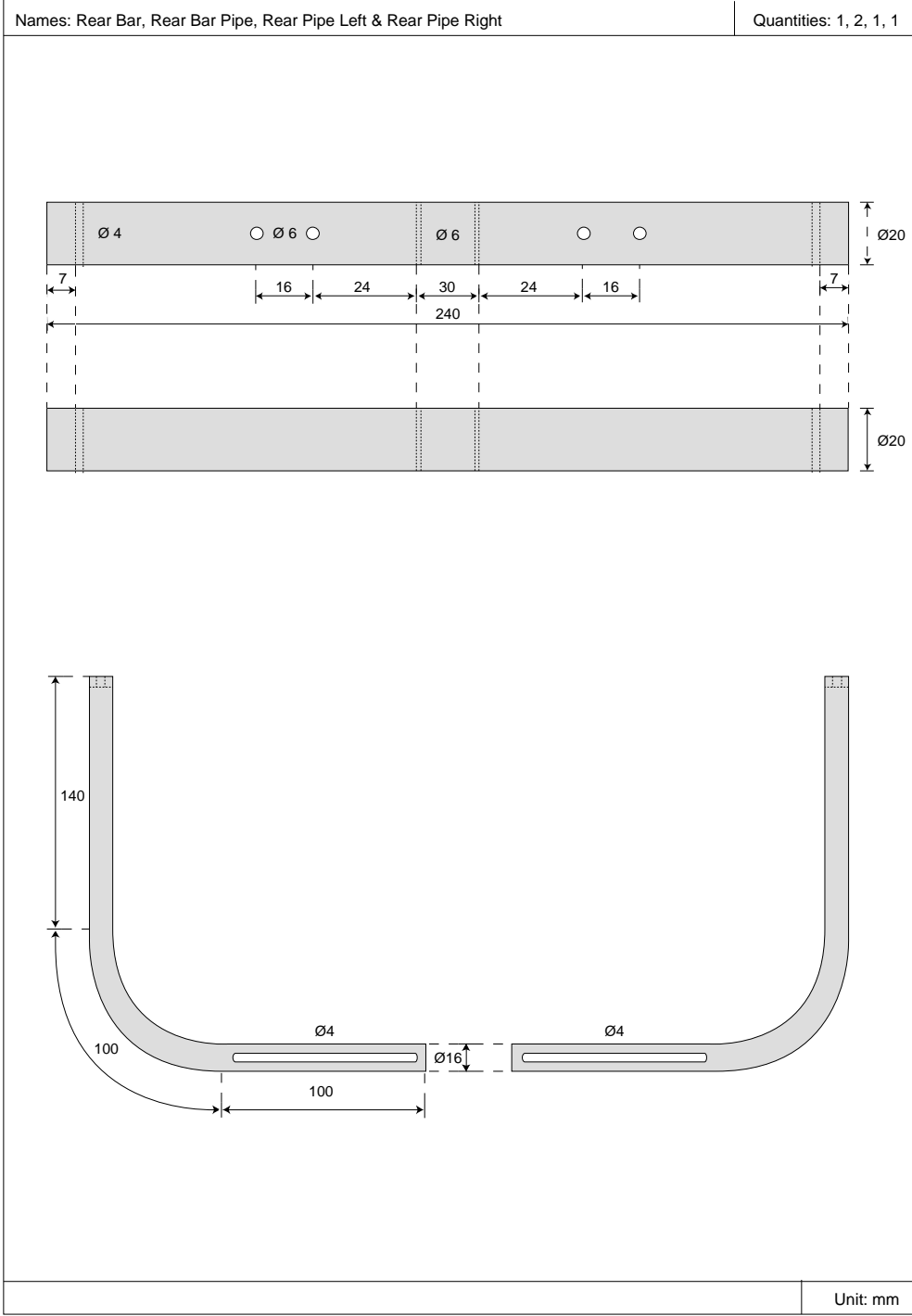
Unit: mm

Names: Plug 1A, Plug 1B, Plug 2, Plug 3A, Plug 3B

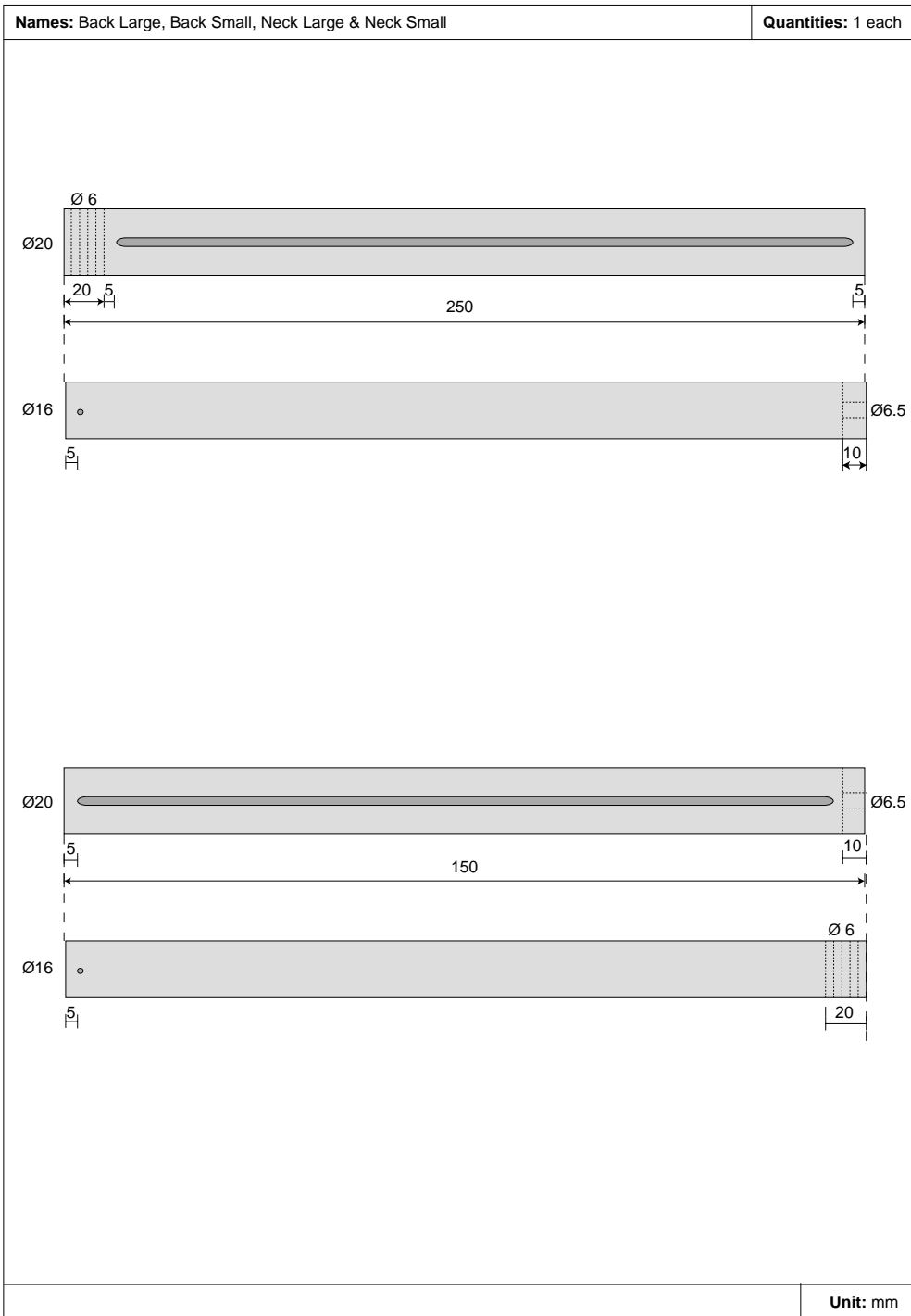
Quantities: 1, 13, 8, 1, 1



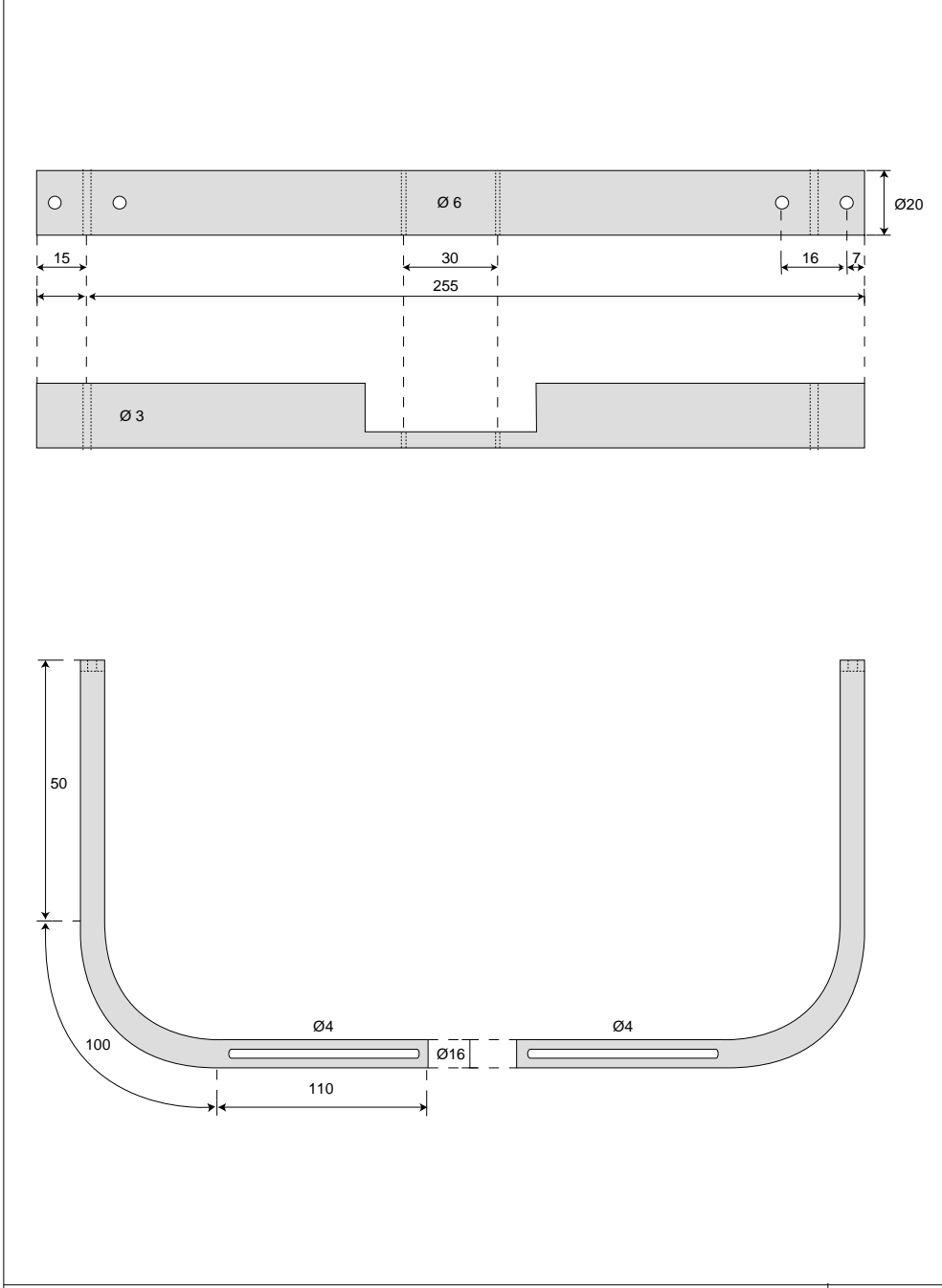
Unit: mm



Unit: mm



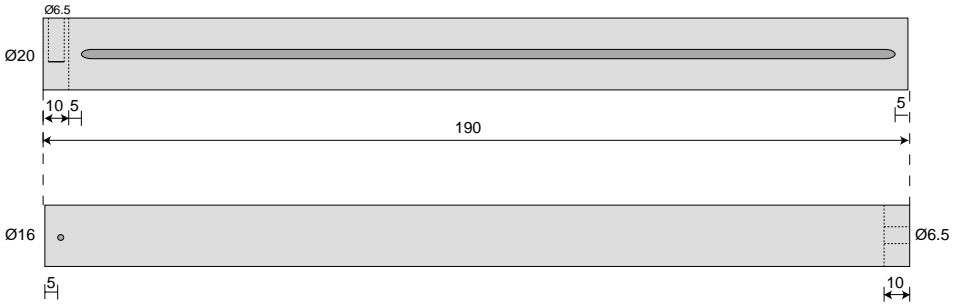
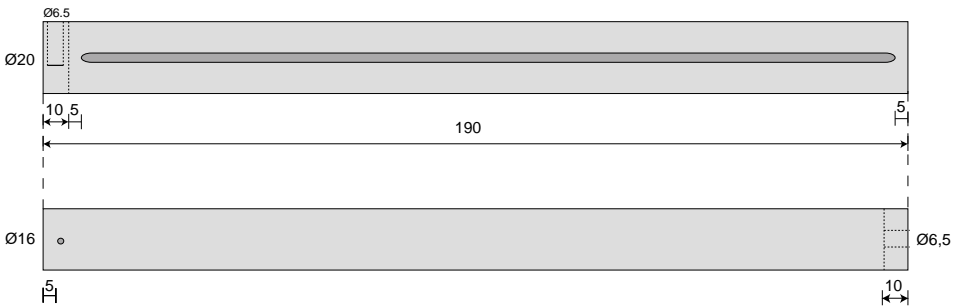
<b>Names:</b> Shoulder Bar, Shoulder Bar Pipe, Shoulder Pipe Left & Shoulder Pipe Right	<b>Quantities:</b> 1, 2, 1, 1
---	-------------------------------



**Unit:** mm

Names: Upper Arm Large, Upper Arm Small, Lower Arm Large, Lower Arm Small

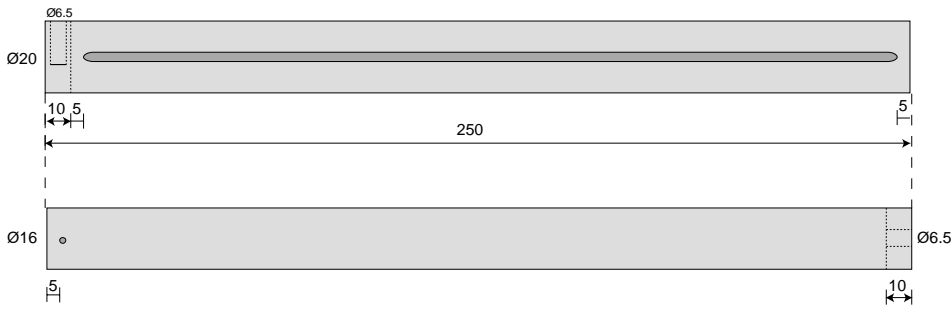
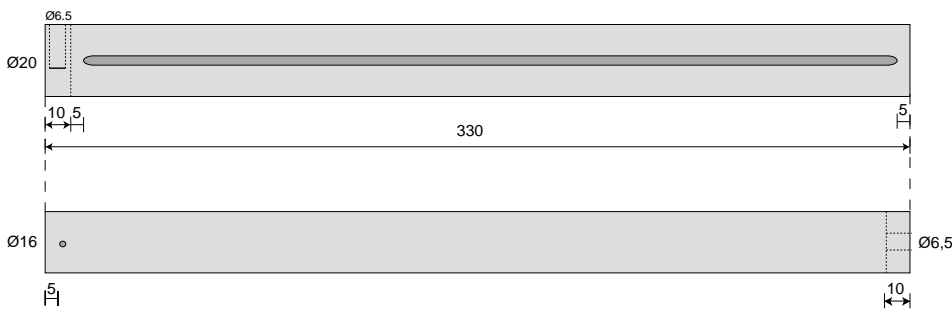
Quantities: 2 each



Unit: mm

**Names:** Upper Leg Large, Upper Leg Small, Lower Leg Large, Lower Leg Small

**Quantities:** 2 each

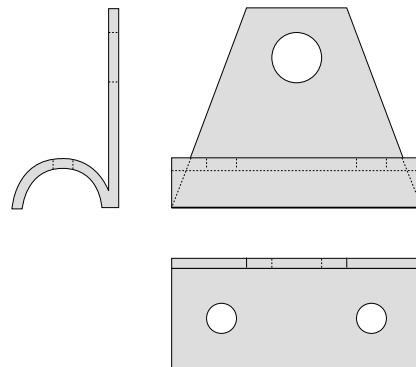
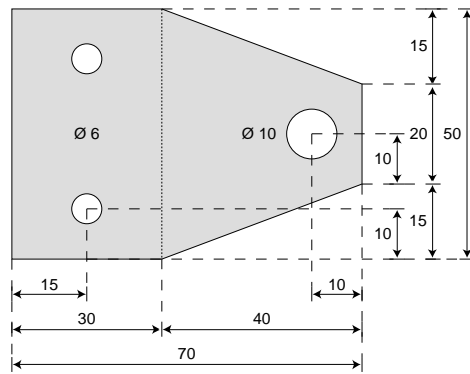


**Unit:** mm



Name: Rear Bar Profile

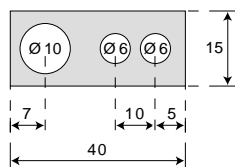
Quantity: 1



Unit: mm

Name: Rear Up & Neck Up Profile

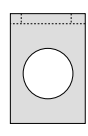
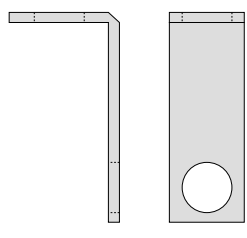
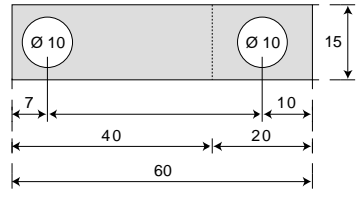
Quantity: 2



Unit: mm

Name: Ankle / Wrist / Shoulder Down Profile

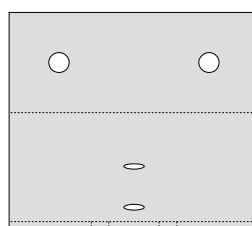
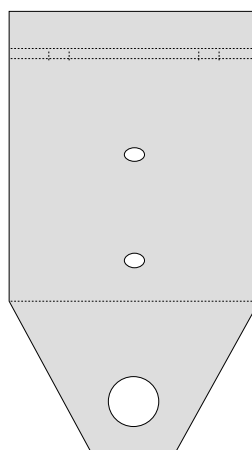
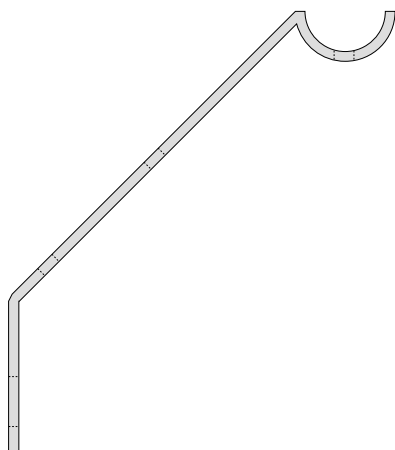
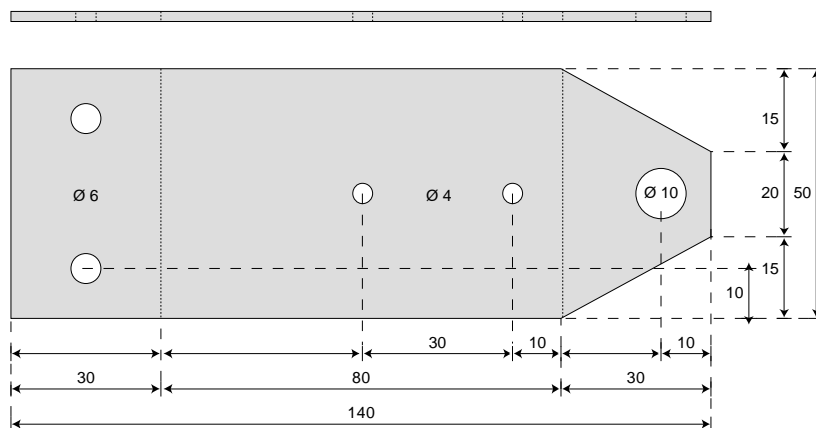
Quantity: 5



Unit: mm

Name: Shoulder Bar Profile

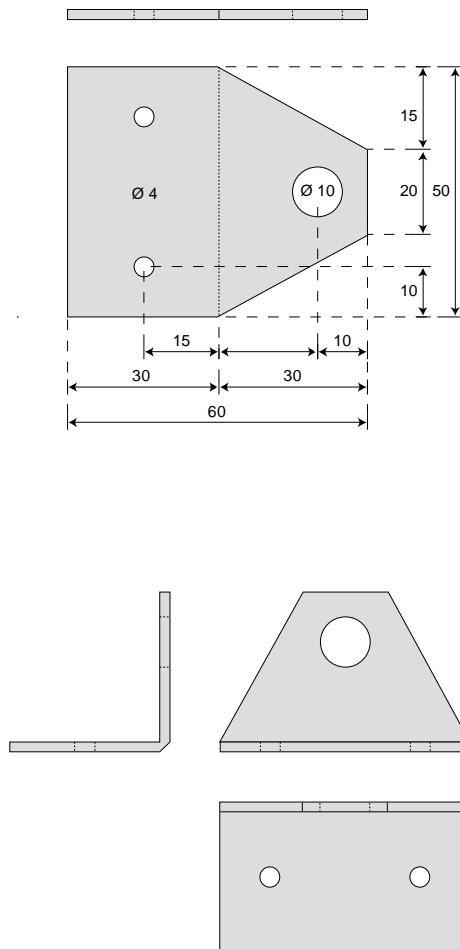
Quantity: 1



Unit: mm

Name: Shoulder Bar Profile 2

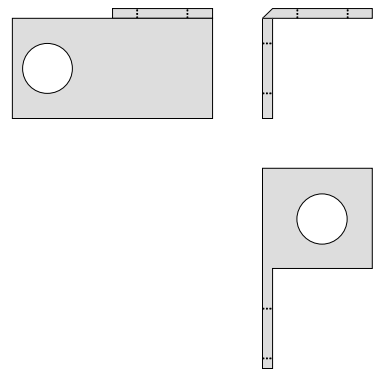
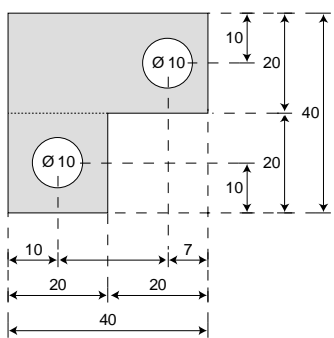
Quantity: 1



Unit: mm

Name: Neck Profile

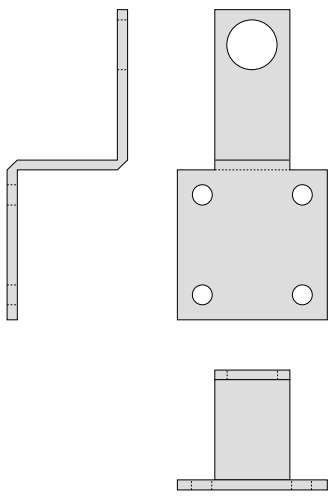
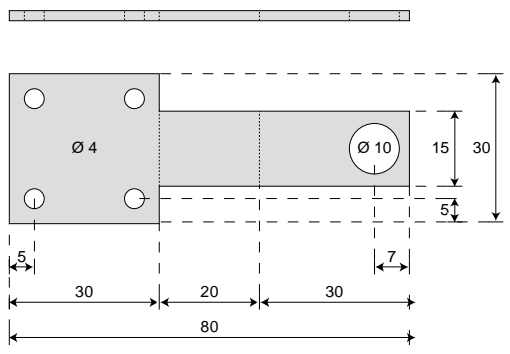
Quantity: 1



Unit: mm

Name: Head Profile

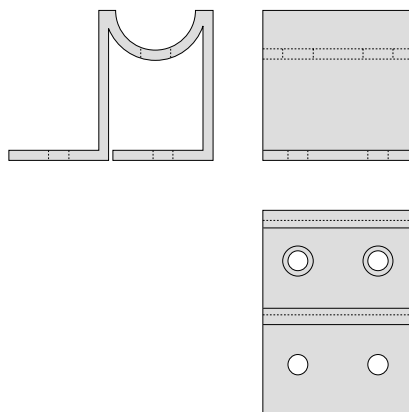
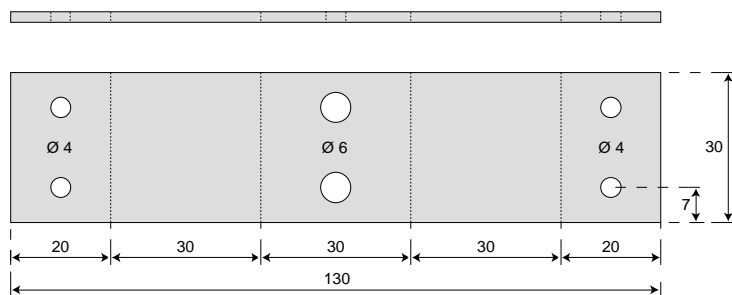
Quantity: 1



Unit: mm

Name: Shoulder Pad Profile

Quantity: 2

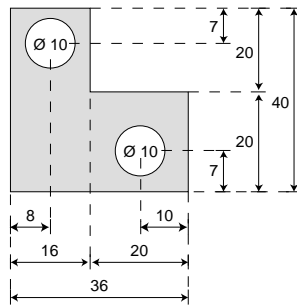


Unit: mm



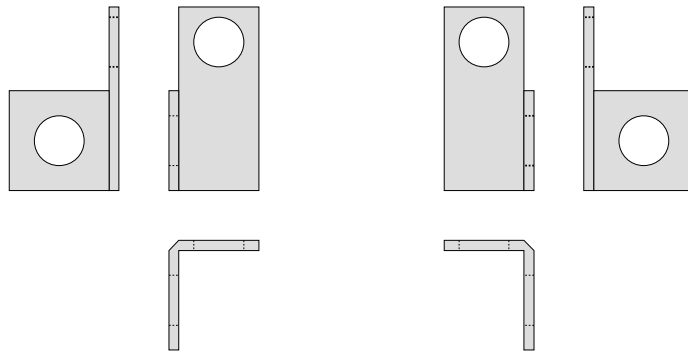
Name: Hip/Shoulder Profile

Quantity: 4



Left

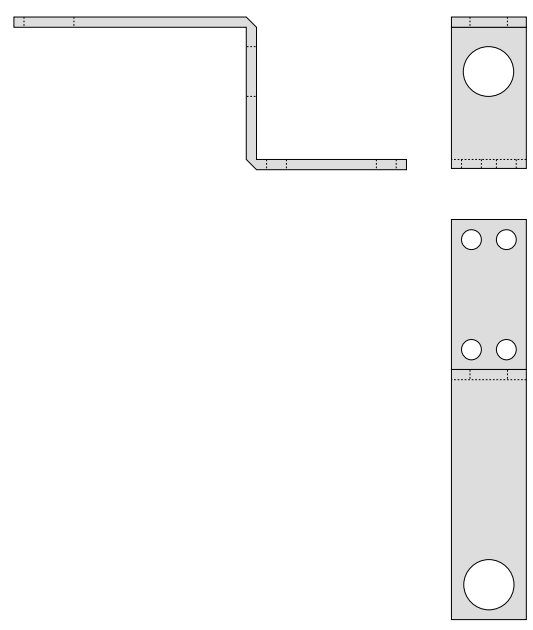
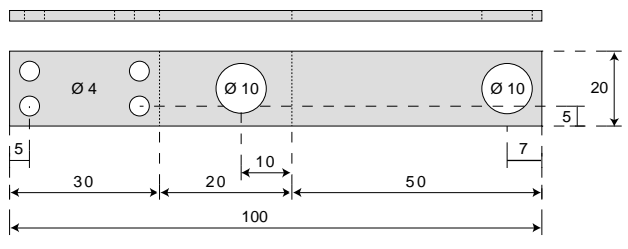
Right



Unit: mm

Name: Elbow Profile

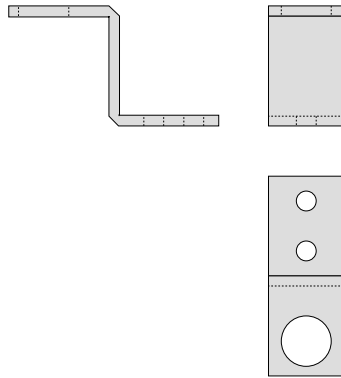
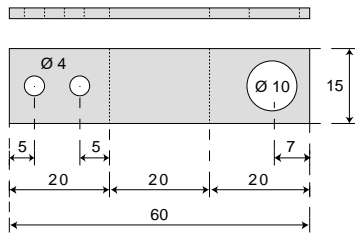
Quantity: 2



Unit: mm

Name: Hand Profile

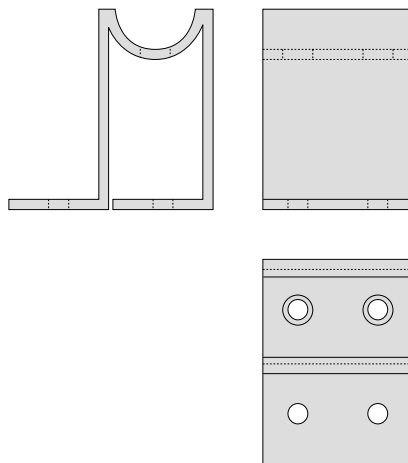
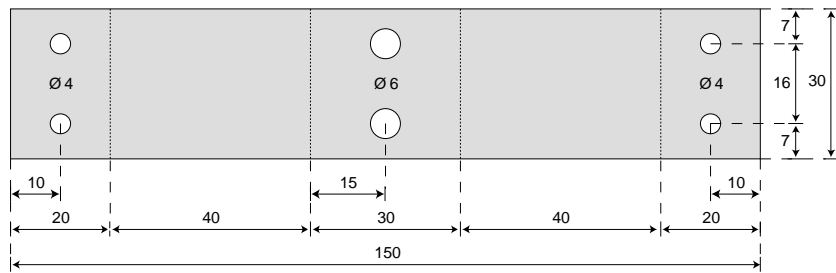
Quantity: 2



Unit: mm

Name: Rear Bar Pad Profile

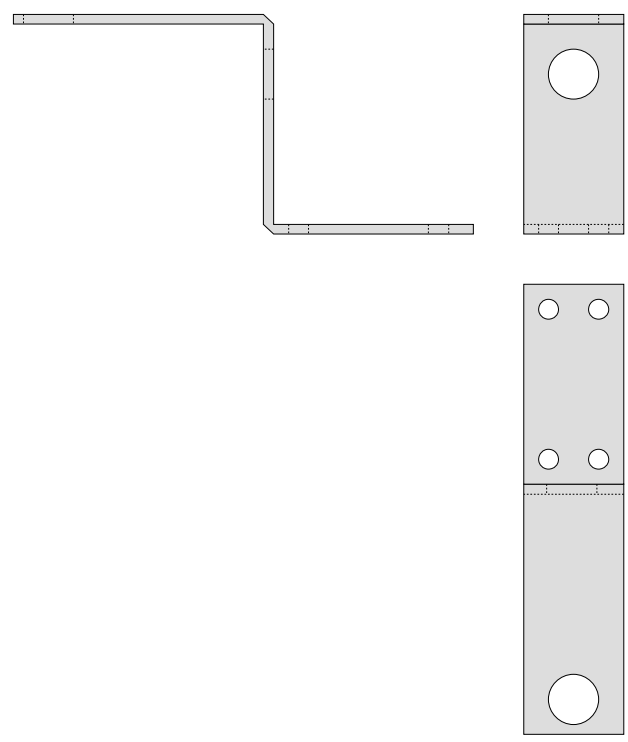
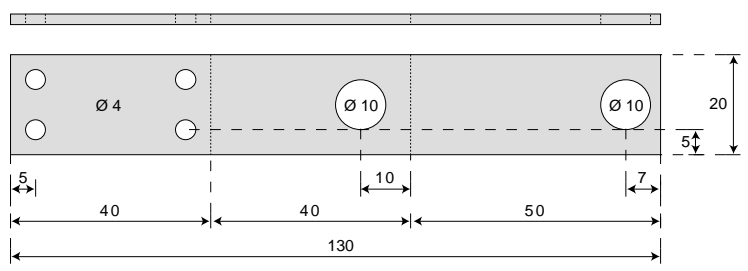
Quantity: 2



Unit: mm

Name: Knee Profile

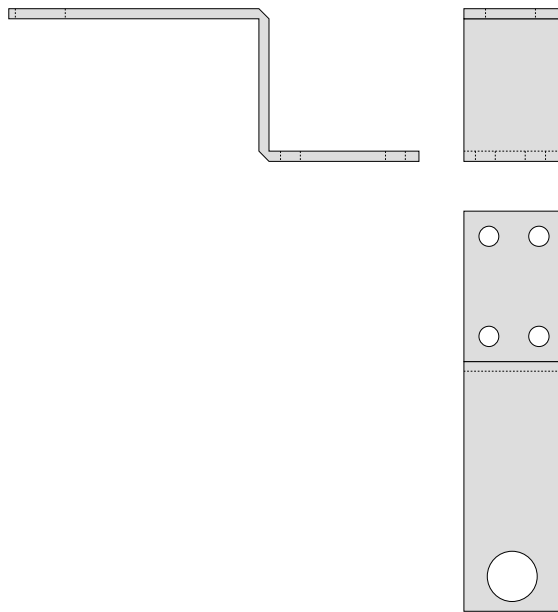
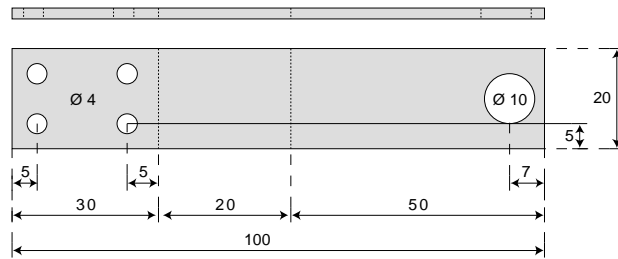
Quantity: 2



Unit: mm

Name: Foot Profile

Quantity: 2



Unit: mm