TALLINNA TEHNIKAÜLIKOOL
MEHAANIKATEADUSKOND

Department of mechatronics

Chair of Mechatronics System

MHK70LT

Oleg Movko

Automation of Photogrammetric Measurement System
Master's Thesis

Author applying for
master's sciences of technical
academic degrees

Tallinn
2016

AUTHOR'S DECLARATION

I hereby declare that this thesis is the result of my independent work.
On the basis of materials not previously applied for an academic degree.
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TUT Department of Mechatronics
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MASTER'S THESIS SHEET OF TASK'S

Year 2016 spring semester

Student: Oleg Movko, 132355
Curricula: MAHM02/13
Spatiality: Mechatronics
Supervisor: Dmitry Shvarts, Chair of Mechatronics Systems, Researcher

MASTER'S THESIS TOPIC:
(in English) **Automation of Photogrammetric Measurement System**
(in Estonian) **Fotogramm-meetria Mõõtesüsteemi Automatiseerimine**

Thesis tasks to be completed and the timetable:

Nr	Description of tasks	Timetable
1.	**Information gathering and literature studying**	**May 2015**
2.	**Measurement's concept and structure design**	**December 2015**
3.	**Calculations, design and selection of drives**	**March 2016**
4.	**Control and electronics design**	**April 2016**
5.	**Thesis compiling**	**May 2016**

Solved engineering and economic problems:
The task of the thesis is to perform automation of photogrammetry measurements of reflector panel of parabolic antenna. Measurement system has to provide RMS value of the reflector panel mirror surface. Choose appropriate drives and control system. Make mechanical drawings of designed structure.

Additional comments and requirements: ….………………………………..........................

Language: English

Application is filed not later than 26.02.2016

Deadline for submitting the theses 20.05.2016

Student Oleg Movko /signature/ ……….............. date 25.02.2016

Supervisor Dmitry Shvarts /signature/ …………..... date 25.02.2016

Confidentiality requirements and other conditions of the company are formulated as a company official signed letter

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EESSÕNA

Käesoleva lõputöö teostati ettevõtte Vertex Estonia AS baasil, kus töö autor töötab konstruktorina. Sellest ettevõttest saadi ka vajalikud kogemused, idee ning vahendid teema lahendamiseks. Tahaksin tänada Vertex Estonia AS tehnikaosakonna liikmeid oluliste soovituste, kaasaaitamise ja motivatsiooni eest.

Selle töö juhendaja on Dmitry Shvarts, Tallinna Tehnikaülikooli Mehhatroonikasüsteemide õppetooli teadur.

INTRODUCTION

The topic of this thesis was found on the facility Vertex Estonia AS (hereinafter referred to as VE) where I am working as a mechanical designer. VE is an engineering plant whose main activities are steel construction and industrial goods fabrication. Principal shareholder of the VE is General Dynamics Corporation which is an American aerospace and defense company. VE fabricates satellite communication earth-station antennas for the company General Dynamics.

Serial products of the VE facility are antennas with the reflector diameter equal to 9 and 13 meters working on the Ka band of the electromagnetic spectrum. Also facility fabricated and participated in designing of such projects as Galileo, MeerKat array, ESOC study of Deep Space Antenna panels. The company employs about 85 people.

Vertex Estonia AS is ISO 9001:2008 certified. The company has Certificate of Manufacturer Qualification for welding works according to ISO 3834. Since 2006 it has been also certified for ISO 14 001 Environmental Management Systems and OHSAS 18 001 Occupational Health and Safety Management Systems [1].

VE has more than twenty years of experience in the manufacturing of reflector panels. Reflector is a main part of the antenna. This is a device that reflects electromagnetic waves. Its shape is a part of a circular paraboloid that is the surface generated by a parabola revolved around its axis. Usually reflectors with diameter higher than two meters are composed of separate reflector panels which are mounted on the antenna backup structure. Panels has to be fabricated with high accuracy of the reflecting surface, which must have a high precision manufacturing level and repeat exactly the shape of a paraboloid given to ensure a functioning and accurate operation of the telescope. VE pays great attention to quality control of the panel fabrication. Average panel surface RMS (root mean square) is about 84 μm.

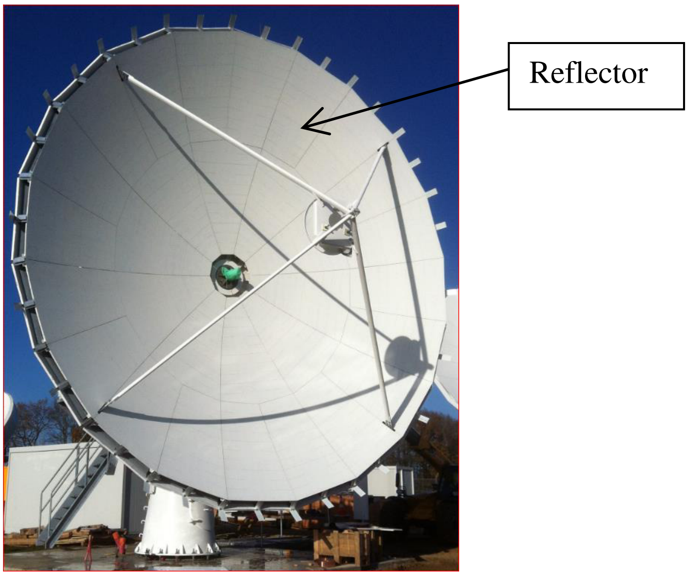


Figure 1.1. Antenna with a reflector diameter 9 meters and two rows of panels

Currently on the facility VE there is a need to measure the reflector panels on a daily basis. Absolutely every panel fabricated by VE should be measured and appropriate report has to be done. Reflector panels are being measured using photogrammetry. Panel measuring is implemented by GSI (Geodetic Services Inc.) “V-STARS” photogrammetry system with usage of “INCA3a+” camera and “PRO-SPOT” projector.

Measuring operator manually aligns the panel and takes photographs from different positions for triangulation method.

Weak points of current measurement procedure are speed, lack of measurement repeatability, manual labor, routine for operator and expensive camera damaging danger. Also the qualification of operator should be quite high what is making measurements dependent on operator availability.

The task of the thesis is to perform automation of photogrammetry measurements of parabolic antenna reflector panel. Measurement system has to provide RMS value of the reflector panel mirror surface. The appropriate drives and control system has to be chosen and mechanical drawings of designed structure has to be prepared.

The success of this study will be measured by the possibility of building automated system on the facility using this thesis.

Photogrammetry measuring system is provided by Geodetic Systems though they don’t provide any automated solutions for measuring. All solutions assume manual photo shooting. No examples were found of automated systems during Internet research.

1. MEASURING OBJECT

Serial products of the VE facility are antenna structures with the reflector diameter 9 and 13 meters. 9 meter antenna has 2 rows of the panels and 13 meter antenna has 3 rows. Idea is to implement automated measuring system to these 5 type panels.

Parabolic reflector is a reflective surface generated by a parabola revolved around its axis (paraboloid). The main parameters of the reflector are outer diameter and its curviness which depends on parabola equation. Usually if the diameter of the reflector is higher than 2 meters then reflector doesn't have monolith construction and consists from segments- reflector panels. Bigger reflectors are divided into the panels because of difficulties of fabrication and transportation. The number of panel rows depends on the reflector diameter. Of course measuring of big areas is more problematic as well.

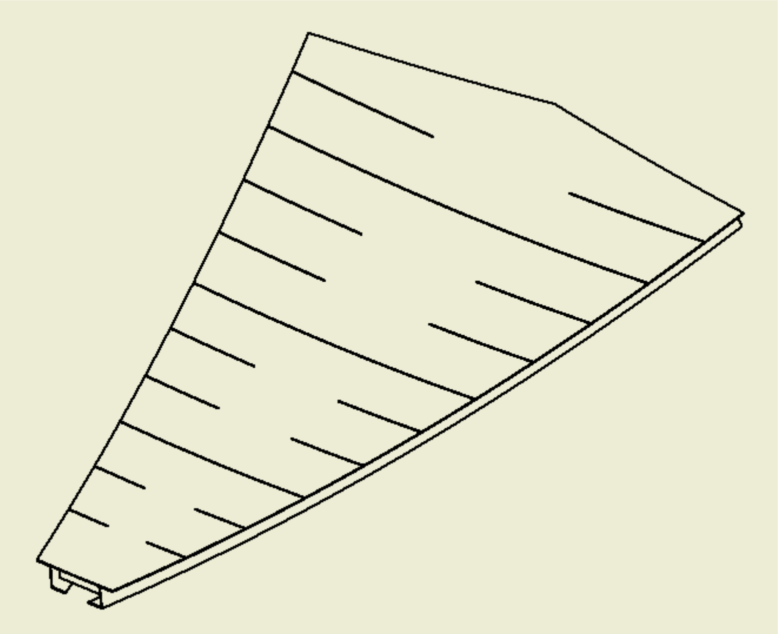


Figure 1.2. Reflector panel isometric view

Panel has a double-curved surface and it is fabricated using special forming tool. Reflector panels are made from aluminum. The mirroring surface is made from 1.6 millimeters thickness aluminum sheet. Panel frame is designed from Z-profiles with a height of 125 millimeters. Z-profiles and aluminum sheet are joined with the putty and 5 millimeter diameter rivets. Z-profiles have transverse cuts with purpose of profile curve possibility. Panel sheets have the longitudinal cuts for the same purpose.

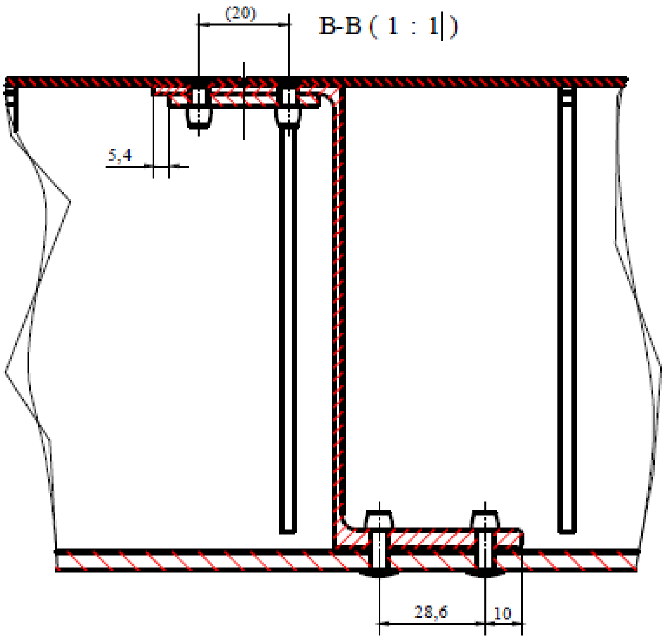


Figure 1.3. Section view of the panel

Fabrication of the panels can be divided into next ten steps:

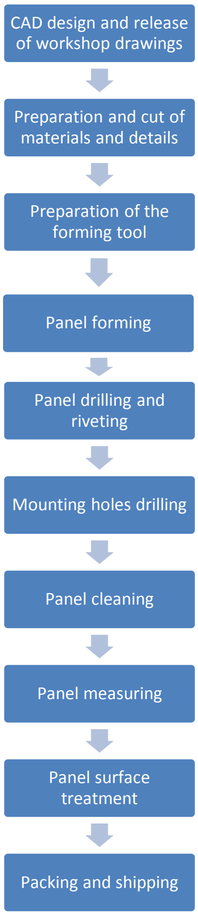


Figure 1.4. Panel fabrication process

The main parameter of the panel is an accuracy of the mirroring surface i.e. how accurately panel surface repeats its segment from the theoretical surface of paraboloid. Measuring of the double-curved surface is very complex problem and it is impossible without using special measuring tools. To implement manual measuring using dial indicators it is necessary to build rotating tool which should replicate certain parabola axial rotation. This tool is very large-dimensioned, resource-demanding and hard achieved of high precision as well the calibration. From the up to date measuring technologies it is possible to single out such systems as laser tracking and photogrammetry.VE facility chose photogrammetry because it is contactless measurement method (accuracy doesn't depend on measurement tool application), which provides possibility of measuring multiple points simultaneously. Also photogrammetry has other advantages which will be described in the next part.

Precision of the surface is characterized by root mean square (RMS) value.

Panels are attached to antenna backup structure by the threaded rods in so called "zero points". These threaded rods allow adjusting zero points in order to set them into nominal paraboloid surface. Compliance of the described adjusting ensures correct antenna work on the required frequency without disturbances. Next figure illustrates how the panel is fixed on the backup structure by the threaded rods.

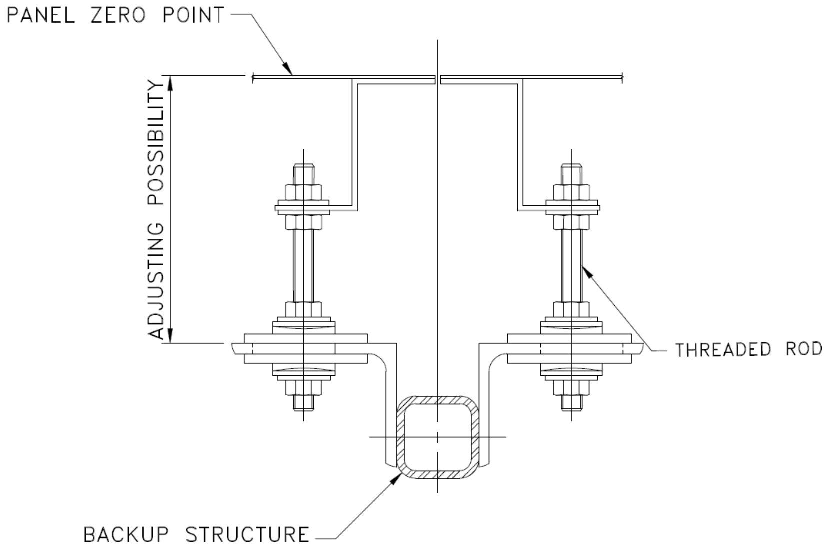


Figure 1.5. Reflector panel fixation on backup structure

2. MEASURING APPROACH

2.1. Photogrammetry

Photogrammetry is a technique used in a metrology to perform measurements of coordinates in three dimensions from photos.

Photogrammetry is widely used in the aerospace, antenna, shipbuilding, construction, and automotive industries for a wide variety of measurement tasks.

The fundamental principle used by photogrammetry is triangulation. By taking photographs from at least two different locations, so-called "lines of sight" can be developed from each camera to points on the object. These lines of sight (sometimes called rays owing to their optical nature) are mathematically intersected to produce the 3-dimensional coordinates of the points of interest. Triangulation is also the principle used by theodolites for coordinate measurement. There are many similarities (and some differences) between photogrammetry and theodolites [2].

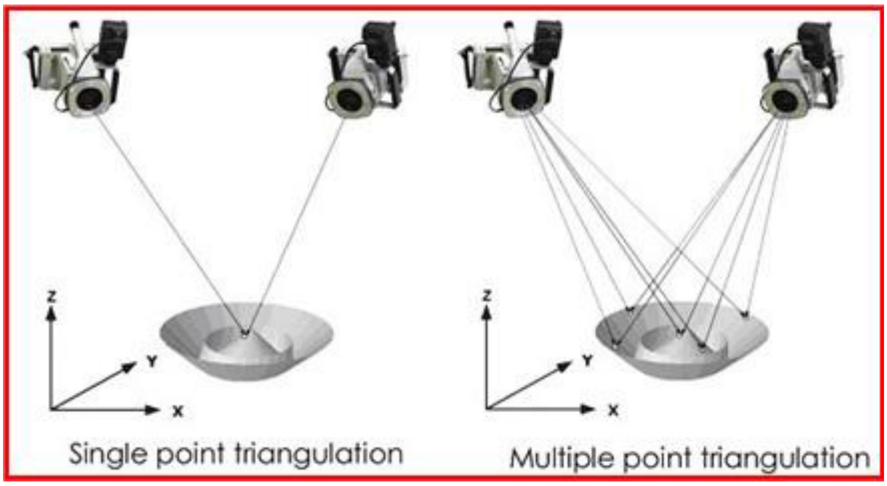


Figure 2.1. Fundamental principle used by photogrammetry

Photogrammetry has many advantages which are enumerated below [3]:

- Photogrammetry is very accurate 3D measurement system (5 µm + 5 µm / m accuracy with a single camera mode).
- Set up time is minimal, no warm up time and fast data acquisition is guaranteed.
- Pictures can be taken in unstable environments (vibration, temperature changes).
- There are no size restrictions of the object to be measured.
- Photogrammetry is suitable for repeat measurements.

- Photogrammetry is excellent for large numbers of points to be measured.
- Photogrammetry systems are portable.

2.2. Measuring tools [2].

2.2.1. System and camera

VE facility uses photogrammetry system provided by Geodetic Services Inc. This is a "V-STARS" measurement system with "INCA 3a+" camera. "V-STARS" system is software which process photographs made by the camera to the 3D measured data. For every measured point are provided x, y and z axis coordinates.

Figure 2.2. "INCA 3a+" camera for industrial photogrammetry

2.2.2. Retro-reflector targets

For the photogrammetry performance it is necessary to make measuring points observable. For this purpose are used special retro-reflector targets. These targets are made from thin (0.11 mm thick) flat, grayish colored retro-reflective material. A low-power flash located at the camera is used to illuminate the targets. The resulting target images are very bright and easy to find and measure. In addition, because the targets are illuminated completely by the flash, the target exposure is independent of the ambient illumination. Pictures can be taken in bright light or total darkness and the target exposure will be the same. This feature makes target exposure very easy [2].

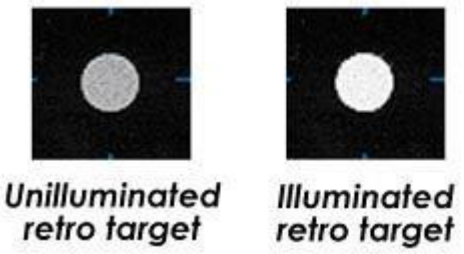

Unilluminated retro target
Illuminated retro target

Figure 2.3. Retro-reflector targets [2]

2.2.3. Scale bar

To scale a photogrammetric measurement, it is obligatory to have at least one known distance. If the actual coordinates are known beforehand of some targeted points, the distances between these points can be computed and used these to scale the measurement. Another possibility is to use a fixture with targets on it and measure this along with the object. The distance between the targets on the bar is known and can be used to scale the measurement. Such fixtures are commonly called scale bars. “V-STARS” use this scale bar to define the size of measuring object comparing with a certain distances between targets on the scale bar [2].

Figure 2.4. Carbon scale bar [2]

2.2.4. Coded targets

Coded targets are a special type of target that the “V-STARS” software can recognize and automatically decode. Each code is made up of a unique pattern of squares and a central dot. Overall dimensions of the panels are as well important as RMS value. To allow measure overall dimensions were designed special corner coded targets. Outline of the each reflector panel can be presented as an isosceles or pentagon. It means that each panel has two equal sharp angles, two equal obtuse angles and one more obtuse angle for pentagon panels. Photogrammetry requires usage of stick targets for the measuring accomplishment but it is impossible to stick the target directly to the vertex of an angle. Designed corner targets have the matching site equals to the corner. Attaching of the corner targets is implemented by spring clamps. For the overall dimensions measurement it is needed to mount corner targets to the each corner and make footage [2].

Figure 2.5. Corner feature targets from the back and front side

Above are shown corner feature targets for the overall dimensions measurements. Targets need to be calibrated for the “V-STARS” recognition.

2.2.5. PRO-SPOT

“PRO-SPOT” projects a dense array of high-contrast targets onto a surface for true non-contact measurement by “V-STARS”.

Through its ability to project targets onto object surfaces such as molds, master models, panels, antennas and other components, “PRO-SPOT” facilitates the fast, accurate and non-contact measurement of 1000s of points on the surface with “V-STARS” in the same time as it would take to measure a few tens of points.

“PRO-SPOT” has next features [5]:

- Fast operation - Single setup measured in minutes with a single-camera “V-STARS” system and in seconds with a multiple-camera system
- Point density - 600 to 23,000 points per setup available
- Portability - Projector weighs less than 6kg and uses a light-weight tripod
- Volume - Measures objects up to 6m in diameter in a single setup
- Durability

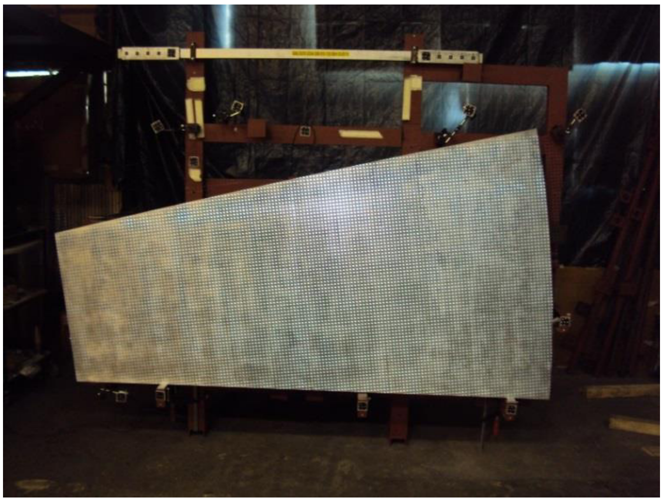


Figure 2.6. Projected points on the panel

The figure 2.6 shows an example of “PRO-SPOT” usage on the panel. Points are projected on the panel and form dense array. The distance between “PRO-SPOT” projector and the panel has to be equal to the panel length. Below on the left figure is shown projector on the tripod in working order. It works according to the controller setup shown on the right figure below.

Figure 2.7. “PRO-SPOT” on the tripod and controller

## 2.3.	Leveling and mounting of the panel

On the antenna backup structure panels are fixed on threaded rods in zero points as it was described in chapter “measuring object”. During the measurement the panel has to be adjusted to the paraboloid nominal surface either. The panel measurement starts with zero points measurements. According to the processed by “V-STARS” data the adjusting is performed. The adjusting is made with a help of digital indicator, which is set directly to the panel zero point (Figure 2.8.).

Figure 2.8. Digital indicator on the panel zero point

2.4. Camera self-calibration necessity

Although the cameras and lenses used in the “V-STARS” system are of the highest quality, they must still be precisely calibrated to remove errors that are present in the system. This ability to calibrate the camera as a byproduct of the measurement is called self-calibration and it means the camera will be calibrated at the time of measurement, and under the environmental conditions that exist (temperature, humidity, etc.) at the time of measurement. This is far superior to relying on an old and possibly outdated laboratory calibration that may have been done under different conditions than existed at the time of measurement.

There are certain requirements that must be met in order to self-calibrate a camera. First, the measurement must have what is called roll diversity. This usually means some photographs have to be taken with the camera horizontal and some with vertical. At least half of all pictures have to be rolled approximately 90 degrees differently than the others.

Figure 2.9. Camera self-calibration [2]

3. MEASURING AT PRESENT

At the present time measuring of the panels is going using photogrammetry system “V-STARS”. Panel is mounted to the special frame in the vertical position. Fixation of the panel to the frame for measurements is made in zero points of the panel. In the Table 2.1 numbers of zero points for each panel are shown.

Table 2.1. Reflector panels

Panel type	Mass, kg	Number of zero points
9M A	30,3	7
9M B	30,2	6
13M A	26,6	5
13M B	45	6
13M C	62	4

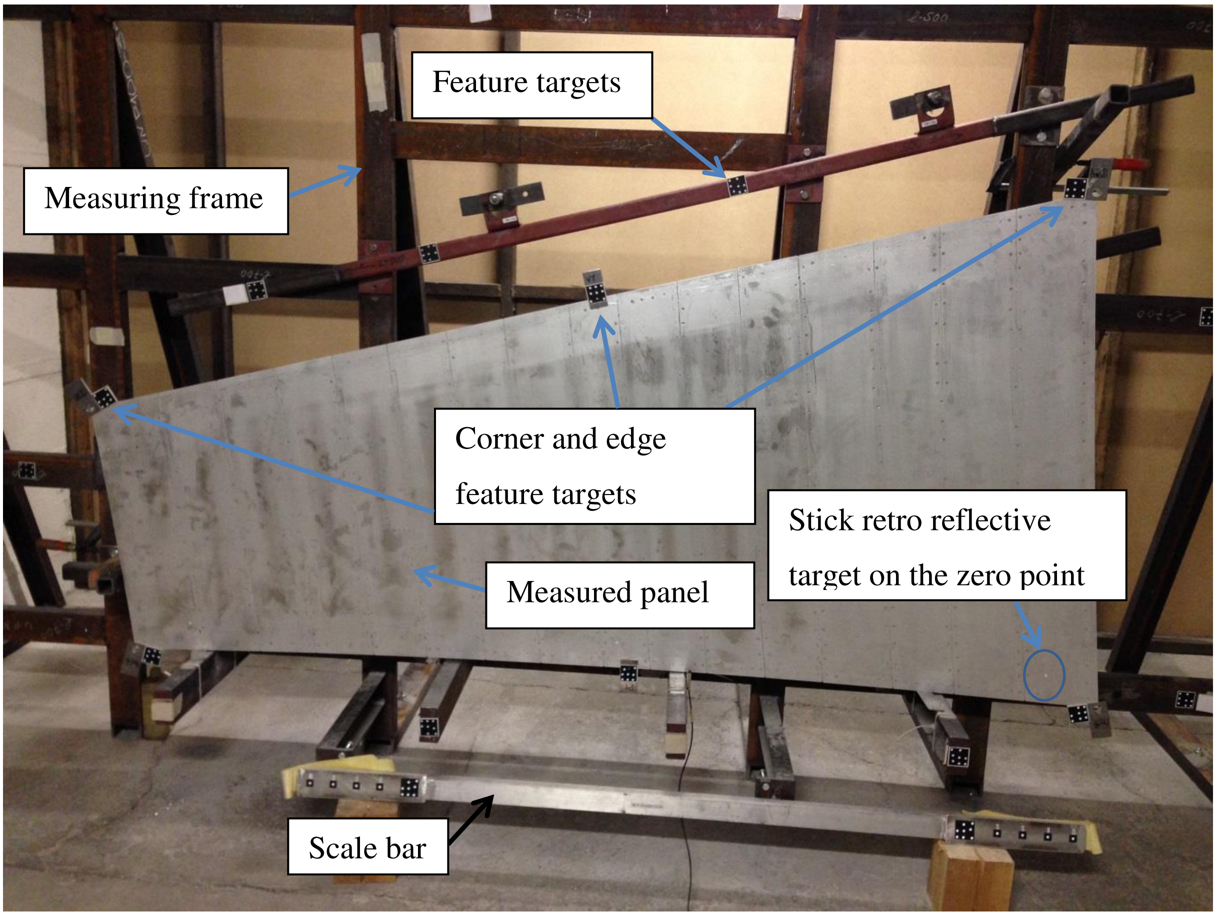


Figure 3.1. Panel on the vertical frame during the measurement

Fixation of the panel is implemented by a clamp with fine thread M12. The whole mass of the panel is concentrated on the horizontal bars under the edge of the panel. Fixation of the zero points is needed only for leveling of the panel surface.

On the frame are attached coded targets for system work capacity. As well there is an attaching point of the scale bar. In consequence of the high price for the carbon fiber scale bars, VE fabricated and calibrated own aluminum scale bars for everyday use.

The process of the measurements can be shown and divided in next steps.

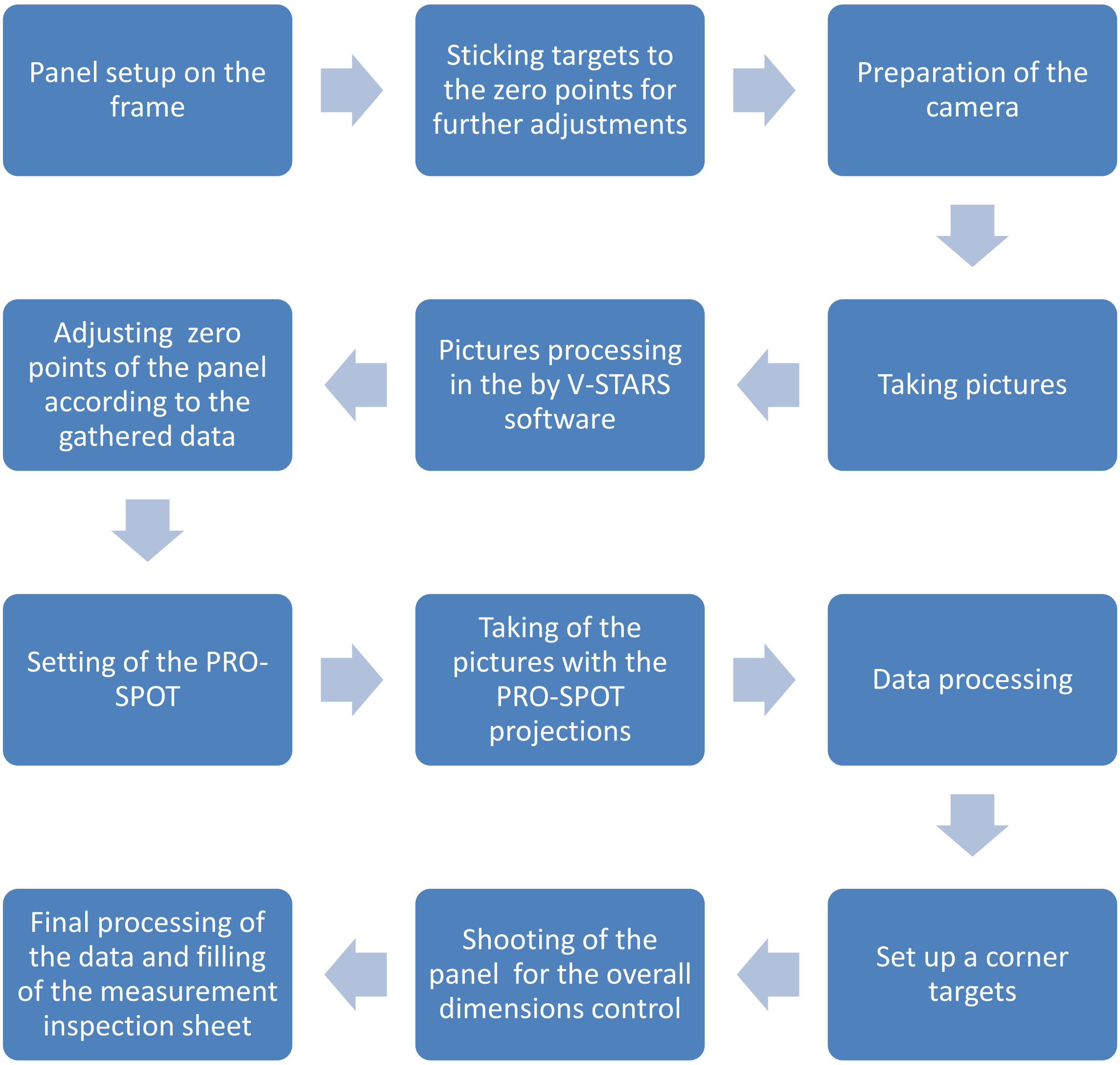


Figure 3.2. Measuring process

Firstly operator puts the panel to the frame and fixes the zero points. On the zero points of the panel should be stick retro reflector targets. This is essential to leveling of the panel surface. Next step is the shooting of the panel for the leveling. Operator has to take about 12 pictures from different sides to ensure the triangulation performance. Taking the pictures has to be done with self-calibration rotation of the camera. Then the pictures are made operator send them to the „V-STARS„ software. Processing of the pictures to the measured data occurs by using prepared script. After that operator analyzes measured data and sees how zero points are out-of-the-way from the theoretical surfaces. Knowing needed distance and direction of aligning operator adjusts zero points by turning screw on the clamps. After the first alignment is performed the second control shooting of the panel must be done. Steps of the shooting and data processing are repeated anew. If the analyzing of the alignment shows sufficient accuracy of adjusting the next step could be performed.

Further steps are already concerned with surface RMS measurements. Firstly “PRO-SPOT” should be set to the proper distance from panel and accordingly focused. During the focusing it is necessary to achieve distinct projections of the points to the panel surface. After the “PRO-SPOT” is installed it is starting the footage of the panel synchronously with “PRO-SPOT” projections. Figure 3.3 illustrates example camera positions during panel surface shooting. Synchronization of the camera footage and “PRO-SPOT” action is built on the photo sensor which reacts on the camera flash.

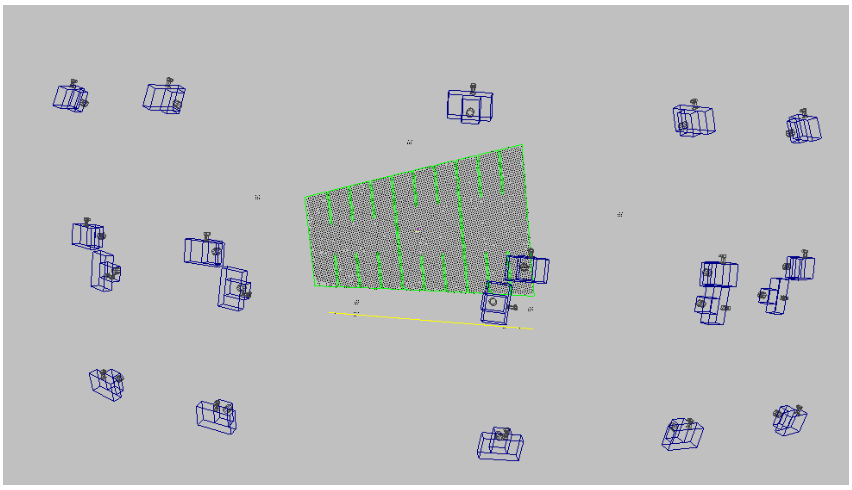


Figure 3.3. Camera positions during panel surface shooting

After all pictures are taken it is started processing of the data. “V-STARS” software processes taken pictures and gives deviation of the measured points from nominal values. RMS value for the panel surface can be calculated using obtained data. As well the range value is given which shouldn’t be higher than 0.61 mm. If RMS value satisfies needed requirements (better than 0.08 mm), operator measures overall dimensions of the panel. For this operation special corner targets are developed. Targets are set to the panel corners and at least 12 pictures from different angles and sides should be taken. Below is brought measuring scheme of reflector panel overall dimensions.

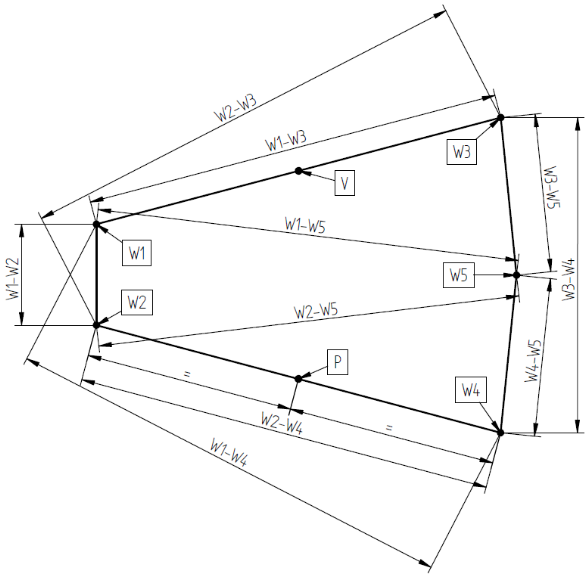


Figure 3.4. Overall dimensions inspection

In the end of measurements acceptance test reports should be filled and signed. For the reports filling simplification and acceleration Excel software is used. Data is imported from “V-STARS” to Excel software.

3.1. RMS value calculation

“PRO-SPOT” projects thousand targets on the panel. For the RMS value calculation it was agreed to use the grid of targets with dimensions 100 x 100 mm. The rest points are considered as redundant and left away. RMS calculation is made by deviations of the measured grid of points from nominal paraboloid panel surface.

$$\mathrm{RMS}=\sqrt{\frac{\sum \Delta^2}{\mathrm{N}}} \tag{3.1}$$

where RMS – root mean square, mm

Δ – deviation of the measured point from the nominal value, mm

N – number of measured points.

4. NEW MEASURING CONCEPTION

4.1. Searching for a new measuring concept

To automate the measuring process first of all the method how to refuse from taking pictures by the operator should be found. Also it is necessary to find how the camera and the measured panel will be disposed.

The camera should be fastened to some manipulator or another object with the ability to move. Concerning to the essential photogrammetry principle as triangulation camera should travel to different places and target to the center of the panel.

The field of view of the camera is 77 degrees by 55 degrees. Regarding this field of view it is possible to find needed camera locations in space. For the measuring model building will be used reflector panel from the serial production with the biggest overall dimensions.

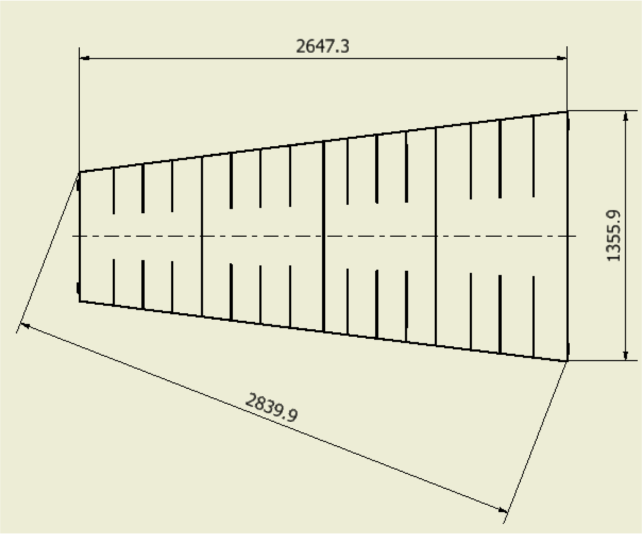


Figure 4.1. Biggest measured panel

Taking pictures manually shows that the biggest distance between camera locations is about 4 meters. Internet research for the manipulators with the required working envelope of maximum reach in 4 meters showed that use of manipulators would be irrational. Manipulators with such working reach are huge and designed for high payloads. While the camera weight equals only to 4 kg. One more problem with the manipulator usage is an intersection with “PRO-SPOT” working area. The scheme given above demonstrates possible solution with manipulator. Unfortunately given system is unjustified and requires extremely high investments.

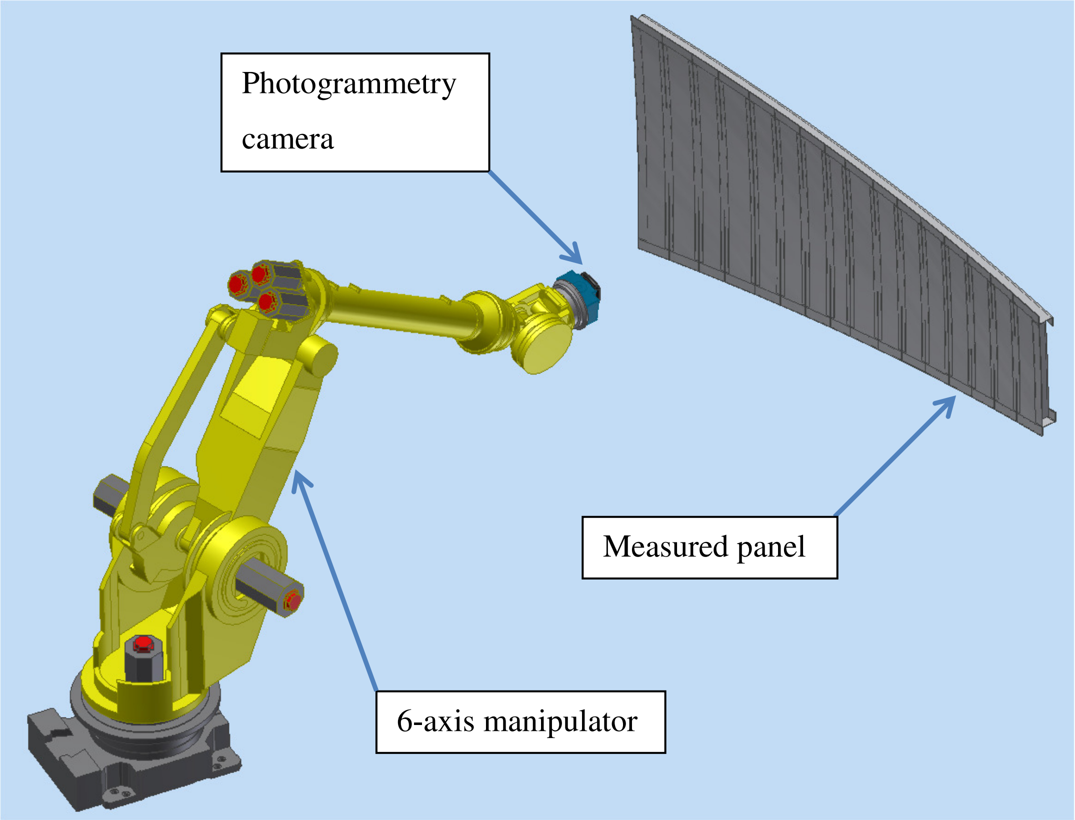


Figure 4.2. Measuring with manipulator

Since the usage of industrial manipulator was declined, there is a certain need to design the specific one. The possible solutions will be observed in the next chapter.

4.2. Possible solutions

There are two logically possible positions of the reflector panel during the measurements: vertical and horizontal (Figure 4.3).

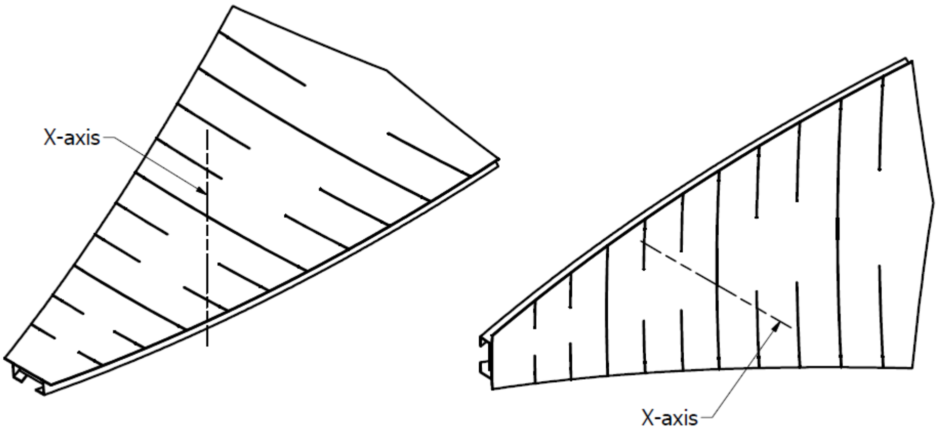


Figure 4.3. Reflector panel in horizontal and vertical position

For the manual shooting putting the panel to the horizontal position was more proper, because this option allows taking pictures standing on the ground without usage of stepladders or scaffolding. As the possible disadvantage of the vertical allocation uneven distribution of the load from the panel's weight could be mentioned. For the measuring in a vertical position the panel has to be placed on the one of the side edges. Vertical way of the panel fastening can cause deformation of the reflecting surface during the measuring what is unallowable for the measurements. The weak point of the vertical position of the measuring object is an inability to take pictures all around due to the limitations by the floor.

In case of a horizontal position of the panel the load is distributed evenly on the all mounting points. To guarantee the proper triangulation performance the angle between panel's middle axis and the camera should be equal to about 70 degrees. Taking into account the field of view of the camera the height of camera can be determined.

If the panel is located in a horizontal position this will give an opportunity to take pictures all around the panel. Below the scheme of taking pictures by rotating the camera around a certain axis is illustrated. This method of measurements has to respond to the photogrammetry fundamental principle- triangulation.

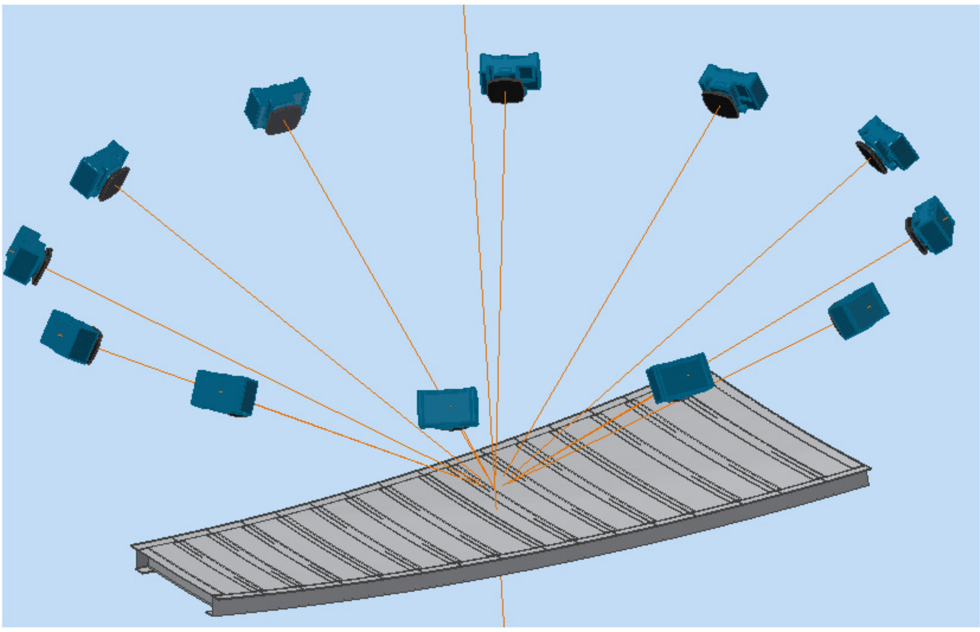


Figure 4.4. Panel in horizontal position and camera shooting positions

4.2.1. Variant with track systems

Using the rail guides with the travel carriage can be proposed as the first possible solution to mount the camera. An example of track system is illustrated on the figure below. For this variant the rails have to be installed near the ceiling in one plane. The camera fastens to the carriage and can be driven around the entire rail way. The main advantage of this structure is the lack of interference with “PRO-SPOT” working area.

As for the disadvantages, the complexity of the rail mounting to the ceiling has to be considered. Another problem is the drive of the carriage. To drive this carriage it is necessary to build a complex system of cable wrap to feed the driven motors. Generally this system demands big money investments.

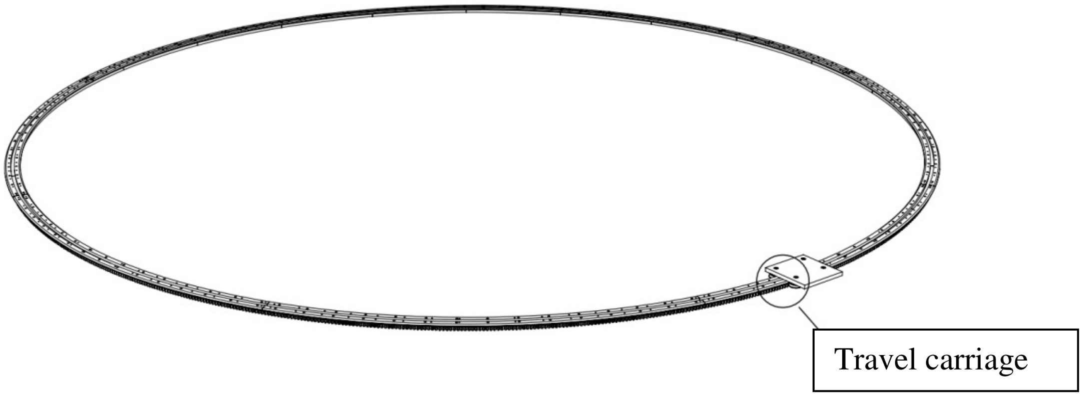


Figure 4.5. HepcoMotion rail guides

4.2.2. Variant with ring slide

Next possible solution is ring slide on the stationary fixed bearings. Example of this system is given on the figure below. This slide is driven by the motor which rotates the rim. The main disadvantage of this structure is the big weight, high cost and the complexity of installation.

Figure 4.6. HepcoMotion ring slide [4]

4.2.3. Cantilever variant

It would be reasonable to use turning cantilever to fasten the camera. The idea is to put rotating cantilever above the reflector panel and while it is making rotation about its axis take pictures every 30 degrees. Cantilever has to be stable and rigid and guarantee the lack of camera fluctuation and vibration. As well the possibility of the camera self-calibration by rotating it around its axis should be implemented.

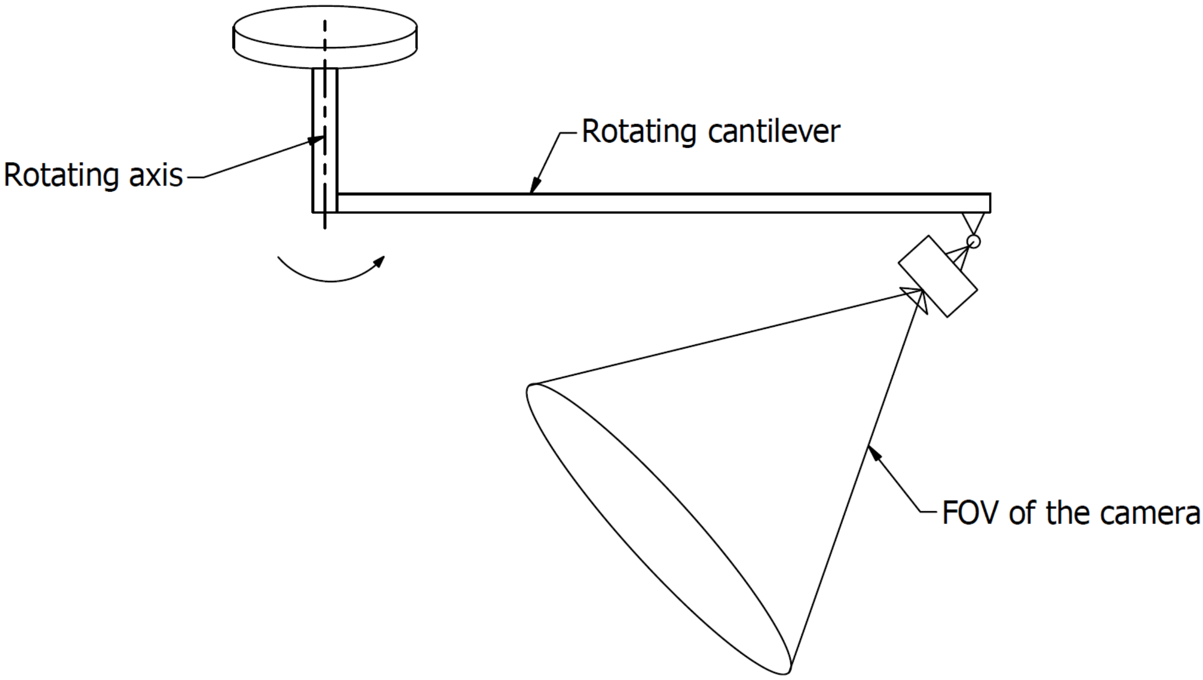


Figure 4.7. Rotating cantilever conception

Rotation of the cantilever will be equal to 360 degrees and after will be reversed. This allows excluding the necessity of the complex cable wrap usage. This system doesn't require any high cost investments and can be manufactured at the VE facility. This rotating cantilever conception is taken as the primary solution.

4.3. New measuring system

The basic dimensions of the turning cantilever and disposition of other parts of the system can be found using graphical method. For the measuring process was chosen proper room. The measuring room layout is plotted to the scheme below (Figure 4.8). Firstly "PRO-SPOT" projector with known working range equaled to 50 degrees was included. The measuring room has an opening in the ceiling what perfectly fits for the "PRO-SPOT" disposition because ceiling height is not sufficient for the proper projection. It means that "PRO-SPOT" projection can be represented as a cone. Measured panel has to be inside of “PRO-SPOT” projection cone. The panel height from the floor was accepted equaled to 0,5 meter. Further there is a need to find a camera positions in a space. Based on the rotating cantilever system cameras were added symmetrically to the rotating axis. The height and cantilever length were found according to the field of view of the camera. As the result the needed height of “PRO-SPOT” equals to 3700 mm, cantilever length is 2000 mm and the camera height from the floor is 2610 mm.

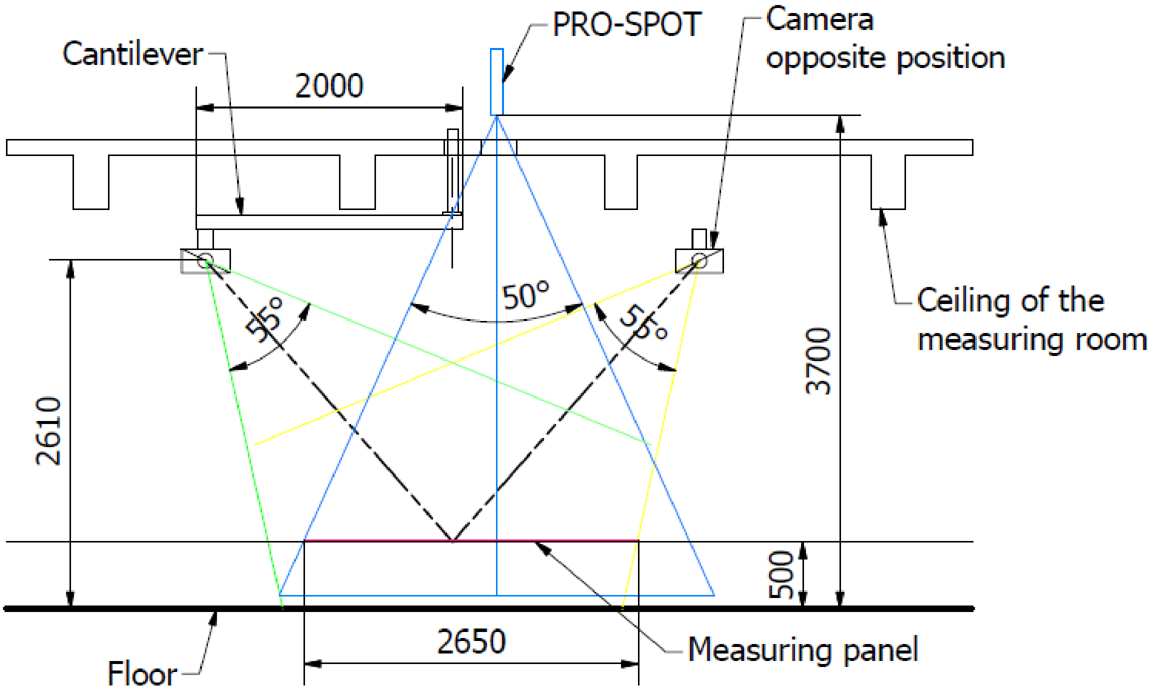


Figure 4.8. Graphical solution

4.3.1. Horizontal panel frame and panel base

Rigid frame was designed with a purpose to hold the panel during the measurements. The frame was designed from the U channel UNP140 which has to provide enough stability during the measurements. This lower frame has to be suitable for mounting the all 5 types of panels.

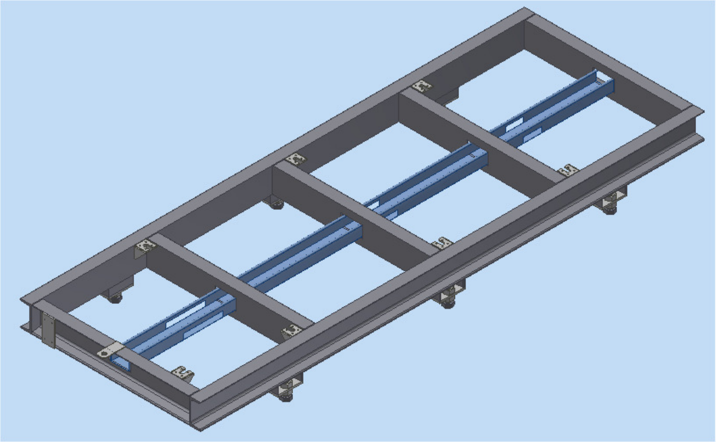


Figure 4.9. Lower frame

In order to meet this requirement supports for each panel, which has to be fasten to the lower frame were designed. These panel supports are located near the zero points of the panel. To measure the certain panel type proper supports have to be used. Changing of the supports on the frame comes by bolted connection. Further in this thesis will be described the way how to mount the panel to supports.

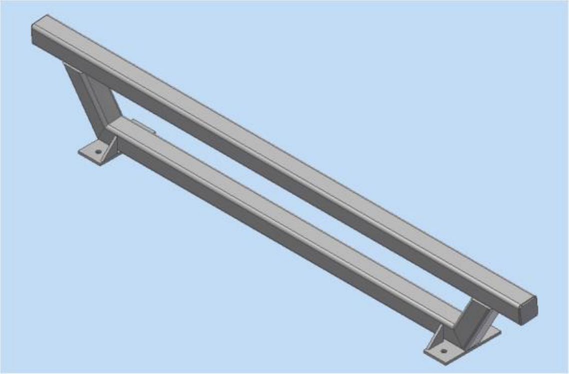


Figure 4.10. Upper panel support

4.3.2. System overview

On the Figure 4.11 is illustrated a new proposed measuring system. Disposition of the parts are done according to the graphically founded dimensions in chapter 3.3. “PRO-SPOT” is located on the second floor and fixed to the stable frame. Opening in the ceiling allows to project targets on the panel in all working range. Rotating cantilever is mounted to ceiling with a little offset from the “PRO-SPOT” middle axis. The offset is needed because of the interference with projection and it is made in direction of the measured panel width, not length. This has to allow the proper projection of the targets on the whole panel surface. The camera is fixed to cantilever end and has possibility of calibration rotation. The lower frame is located directly under the “PRO-SPOT”. On the universal lower frame are mounted panel supports for a certain panel type. Totally system has two drives: rotation of the cantilever (Drive 1) and camera calibration rotation (Drive 2).

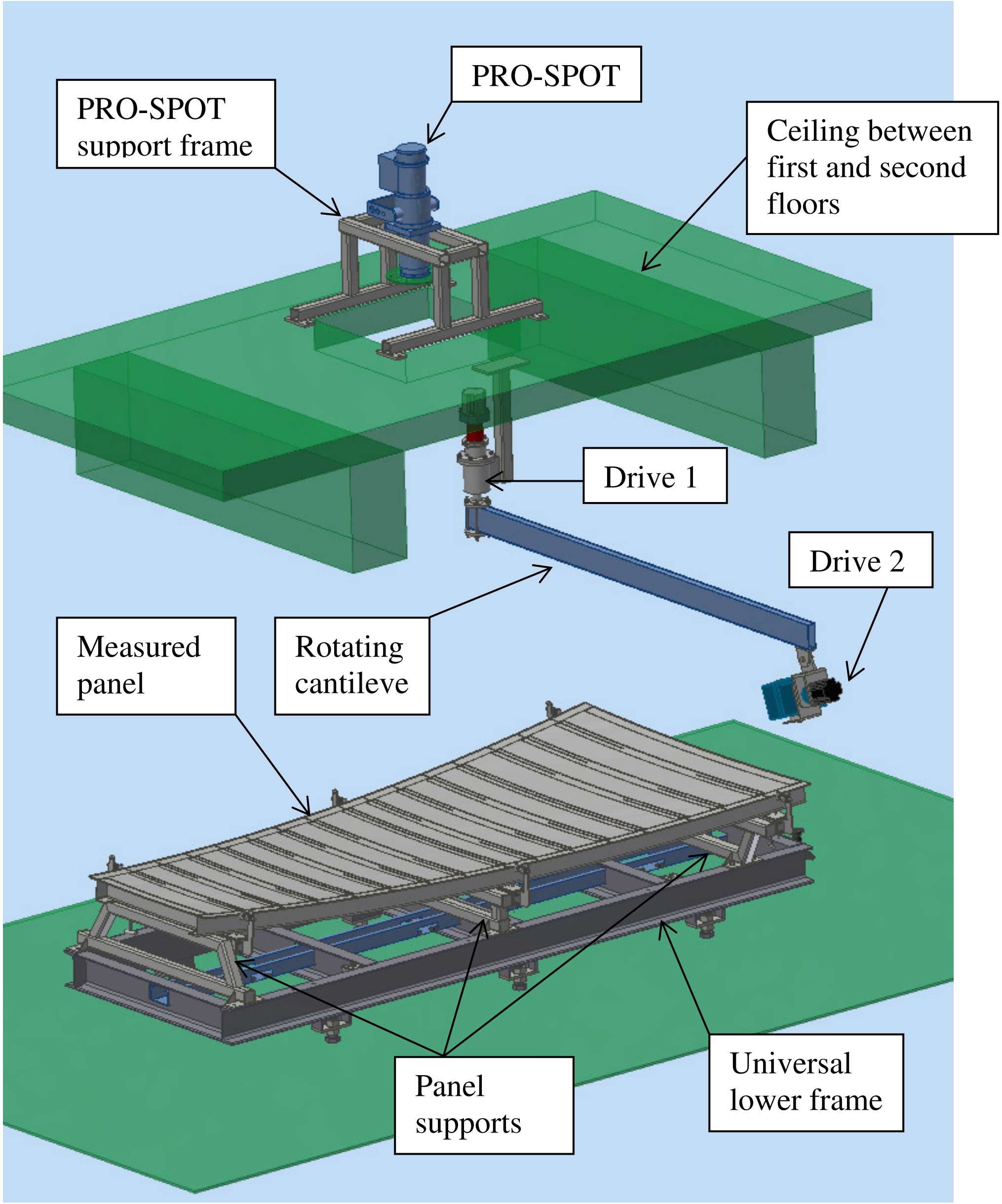


Figure 4.11. Measuring system concept

5. ROTATING CANTILEVER

5.1. Cantilever structure and design

Below is shown proposed design of the rotating cantilever. The cantilever is fixed to the steel shaft. Shaft rotates on the bearings, which are placed to the housing. Between bearings is installed distance bush. The upper bearing is fixed in the housing by internal retaining ring. The shaft is fixed by the shoulder from the lower part. There is a thread on the upper part of the shaft and it is tightened by the lock nut. Tooth lock washer is added to the structure as a screw locking device.

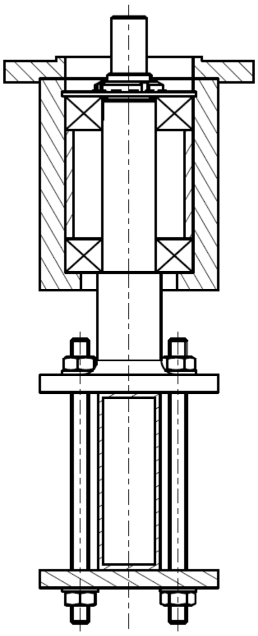


Figure 5.1. Rotation cantilever

5.2. Cantilever structure and design

Due to the high demands on the rigidity and stability of the camera, the cantilever has to be made from the rigid profile. There shouldn't be any oscillations when the cantilever is stopped after the rotation. Otherwise the synchronization is not possible with the "PRO-SPOT". Cantilever could be considered as a beam with a fixed support only from the one end. There is acting the load of the camera on another end of the beam. Deflection of the beam can be calculated using next formula [6]:

$$f = \frac{F \cdot l^3}{3 \cdot E \cdot I} \tag{5.1}$$

where f – deflection of the beam, mm,

l – length of the beam, l=2 mm

E – elastic modulus; E=70000 N/mm^2 for the aluminum, E=200000 N/mm^2 for the steel

I – second moment of area, mm^4

F – bending force, F=60 N

The main target is to find the profile with high rigidity and low weight. Putting to heavy beam will lead to the bigger moment of inertia of the system causing the choice of the more powerful drive. As well the load on the pivot would be greater. Choosing the material aluminum would be more preferable due to the smaller density. The deflection of the aluminum rectangular tube with dimensions 100 x 35 x 3 mm will be controlled. The weight of the tube is 2 kg/m. Firstly the second moment of area of the profile should be calculated.

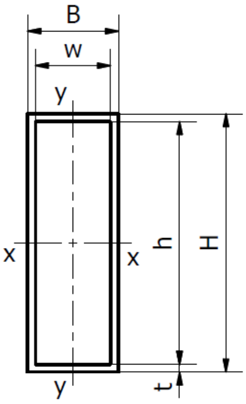


Figure 5.2. Rectangular tube

The formula for the structural shape as a rectangular tube is:

$$I_x = \frac{B \cdot H^3 - w \cdot h^3}{12} = \frac{35 \cdot 100^3 - 29 \cdot 94^3}{12} = 909422\ mm^4 \tag{5.2}$$

Deflection of the beam will be:

$$f = \frac{60 \cdot 2000^3}{3 \cdot 70000 \cdot 909422} = 2\ mm \tag{5.3}$$

A steel tube dimensions with the approximately equal weight 2,36 kg/m are 40x20x3 mm. Checking the deflection for this section:

$$I_x = \frac{B \cdot H^3 - w \cdot h^3}{12} = \frac{20 \cdot 40^3 - 14 \cdot 34^3}{12} = 60812\, mm^4 \tag{5.4}$$

$$f = \frac{60 \cdot 2000^3}{3 \cdot 200000 \cdot 60812} = 13\, mm \tag{5.5}$$

Finally aluminum profile is more than six times rigid than the steel mass equal one.

5.3. Bearings sizing and selection

The weight of the structure will act on the bearings. Bearings will take load from the weight and also the static moment. Firstly should be considered the equilibrium of the system. The mass of the system can be divided in two components: the mass of the camera module M and cantilever mass m. The mass of the cantilever is known and we can substitute it as vertical force P_C acting on the middle of the cantilever, because there is a center of gravity of the cantilever. The mass of the camera module is substituted as force P_L. If we have two bearings, the reaction of one of them could be divided in two composing reactions Y_A and X_A. Reaction of the second bearing is given as horizontal force R_B. The reactions are shown on the figure below.

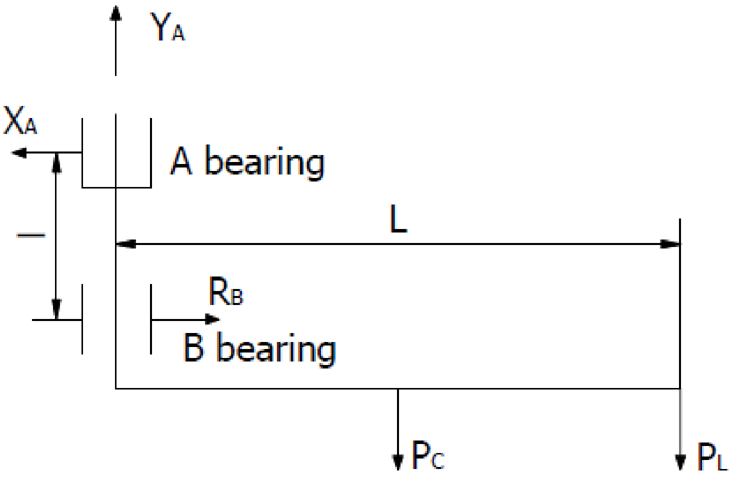


Figure 5.3. Bearings reaction

Finally to the structure is applied planar system of five forces and there are three of them indeterminate. Applying to the system analytical terms of equilibrium and Varignon's Theorem three equations could be equated [7]:

$$\sum M_A = 0;\ +R_B \cdot l - P_C \cdot \frac{L}{2} - P_L \cdot L = 0, \tag{5.6}$$

$$\sum X = 0;\ -X_A + R_B = 0, \tag{5.7}$$

$$\sum Y = 0;\ Y_A - P_C - P_L = 0, \tag{5.8}$$

where P$_C$ – gravity of the cantilever, $P_c = m \cdot g$,

P$_L$ – gravity of the camera module, $P_L = M \cdot g$,

M – mass of the camera module, M = 6 kg,

m – mass of the cantilever bar, m = 4 kg,

L – length of the cantilever, L = 2 m,

l – distance between bearings, l=0,08 m.

Solving the equation it is possible to calculate R$_B$:

$$R_B = \frac{P_C \cdot \frac{L}{2} + P_L \cdot L}{l} = \frac{4 \cdot 9{,}81 \cdot \frac{2}{2} + 6 \cdot 9{,}81 \cdot 2}{0{,}08} = 1962\ N \tag{5.9}$$

Knowing the R$_B$ value it is possible to get Y$_A$ value:

$$X_A = R_B = 1962\ \text{N} \tag{5.10}$$

According to the third equation Y$_A$ value can be founded:

$$Y_A = P_C + P_L = 4 \cdot 9{,}81 + 6 \cdot 9{,}81 = 98{,}1\ N \tag{5.11}$$

According the calculations above the radial loads for the both bearings are equal. The axial load is very small and technically can be divided evenly on two bearings or implemented only to the upper bearing. Suitable type of the bearings is deep groove ball bearing. These bearings take radial load. The axial load is allowed for them as well [8].

Bearing selection is made basing on the taken shaft and housing diameters. Suitable deep groove ball bearing according to the shaft diameter d 30 mm and the housing diameter 72 mm is SKF 6306 which corresponds to the DIN 625 standard. The static load of the selected bearing is 12000 N and it is multiple times more than the needed value.

5.4. Shaft design

On the shaft are acting forces of the gravity and as well the bending moment. The gravity force is leading the shaft to the expansion and leading to the tensile stress. The axial acting load on the shaft calculated in the previous chapter is 98,1 N. This is a very small load and the tensile stress can be neglected. The biggest stress is on the contact point of the shaft and lower bearing, due to the maximum bending moment in this point.

Bending stress can be calculated using next formula:

$$\sigma_b = \frac{M_b}{W} \tag{5.12}$$

where σ_b – bending stress

M_b – bending moment

W – section modulus

Shaft has a circle cross-sectional shape with diameter d and section modulus can be calculated according to the formula:

$$W = \frac{\pi \cdot d^3}{32} = \frac{\pi \cdot 30^3}{32} = 2649\ mm^3 \tag{5.13}$$

where d – shaft diameter; d= 30 mm.

Bending moment can be found according to the scheme below (Figure 5.4.). Bending moment will be equal:

$$M_b = P_C \cdot \frac{L}{2} + P_L \cdot L = 4 \cdot 9{,}81 \cdot \frac{2}{2} + 6 \cdot 9{,}81 \cdot 2 = 157\ N \cdot m \tag{5.14}$$

Calculating the bending stress:

$$\sigma_b = \frac{157 \cdot 10^3}{2649} = 59{,}2\ N/mm^2 \tag{5.15}$$

For the S235 steel allowed bending stress σ_{allow} equals to 330 N/mm^2. The factor of safety υ of the shaft equals to:

$$\upsilon = \frac{\sigma_{allow}}{\sigma_b} = \frac{330}{59{,}2} = 5{,}6 \tag{5.16}$$

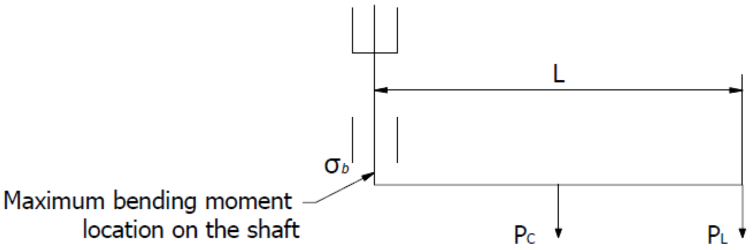


Figure 5.4. Bending moment of the shaft

Performed calculation shows that the selected shaft diameter is acceptable.

5.5. Estimation of frictional moment

Under certain conditions the frictional moment can be calculated with sufficient accuracy using a constant coefficient of friction μ from the following equation:

$$M = 0{,}5 \cdot \mu \cdot F \cdot d = 0{,}5 \cdot 0{,}0015 \cdot 1962 \cdot 0{,}03 = 0{,}04\ Nm \tag{5.17}$$

where M – frictional moment,

μ – coefficient of friction for the bearing; μ=0,0015 [8] for the deep groove ball bearings,

F – bearing load, F=1962 N

d – bearing bore diameter, d= 0,03 m

Finally frictional moment has very small value and it could be neglected in the needed rotating moment calculation.

5.6. Camera calibration rotation

As it was described in chapter 2.4 there is a need of camera rotation for the calibration purpose. Middle axis is aimed directly to the center point of the measured panel during the normal measuring position of the camera. To keep the camera axis aim stable the camera has to revolve around its axis. For calibration 90 degree rotation is needed. On the scheme below is shown the proposed camera calibration approach.

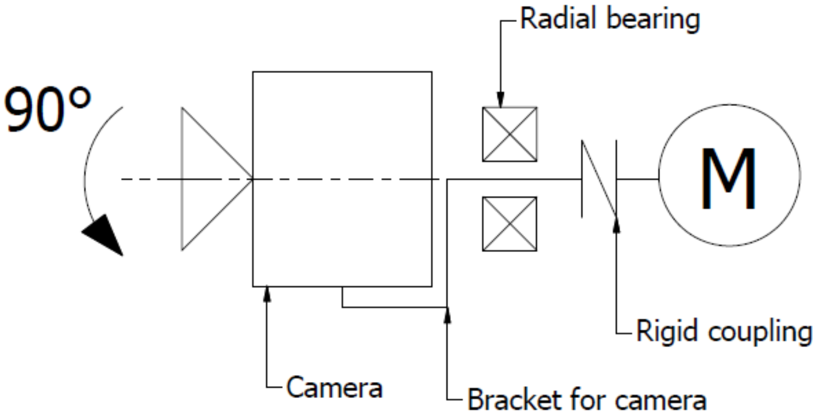


Figure 5.5. Schematic calibration assembly

The standard camera fastening can be used for this purpose by designing the special bracket. The rotation of the bracket is implemented on the shaft, which is rotating on the bearing. The motor is connected to the shaft by the rigid coupling.

5.7. Experimental data gathering

To control proposed measuring system concept was decided to build experimental plant. For this purpose was designed and fabricated test cantilever for the camera. Test cantilever was mounted to the ceiling of the measurements room. Under the test cantilever measured panel was fixed up and set to the test frame in a horizontal position. Measuring room has the opening in the ceiling which was ideally suitable for the “PRO-SPOT” mount. To connect the camera to the cantilever head from the tripod was used.

Figure 2.6. Test rotating cantilever for the camera

Owing to the test measurements the proper dynamics of the cantilever was obtained. The angular velocity of the cantilever was taken equal to 1 revolution per minute.

The main purpose of the test was successfully achieved: measurement via cantilever is possible. Measurements gave the final value, but with the big error. The main problem during the measurements was unstable position of measured panel, because of the unprepared base. Test measurements showed propriety of the proposed system development.

6. PANEL MOUNTING AND LEVELING

The previous mounting and leveling tooling doesn’t respond to the requirements. The new design of the tooling will be described below.

6.1. Panel leveling tooling design

The previous clamping mechanism had many problems. The main problem is that it is impossible to save the previous adjustments while the clamp loses its place. The second problem is the unequal clamping force on the different clamp and as well the lack of repeatability of the clamping force. Time-consuming use can be named as the third problem, while the adjustment is uneasy as well.

Based on the listed problems new leveling tooling was designed. Toggle clamp has to leave out the problem of unequal clamping force. Using the toggle clamp has to make the process faster and more reliable as well.

With the object of save the adjustments during the changing of reflector panels bearing mechanism which allows the linear movement of the clamp was designed. The housing item 5 on the Figure 6.2 is fastened with the nut item 7 to the stationary bracket. The adjustment nut item 4 can be rotated concerning item 5. Inside of the adjustment nut there is a fine thread M12x1,5 which allows the rotation on the threaded rod item 3. As the result the rotating of the nut item 4 inside the housing leads to the linear movement of the threaded rod with the toggle clamp.

As the screw fine M12x1,5 thread is used. The thread pitch is the distance between threads expressed in millimeters and showed what length the nut will be driven by the 360 degrees rotation. If the adjustment has to be made by the l_A mm, the nut has to be rotated on the certain angle α. This angle can be calculated using next formula:

$$\alpha = \frac{l_A \cdot 360}{s} \tag{6.1}$$

where s – thread pitch

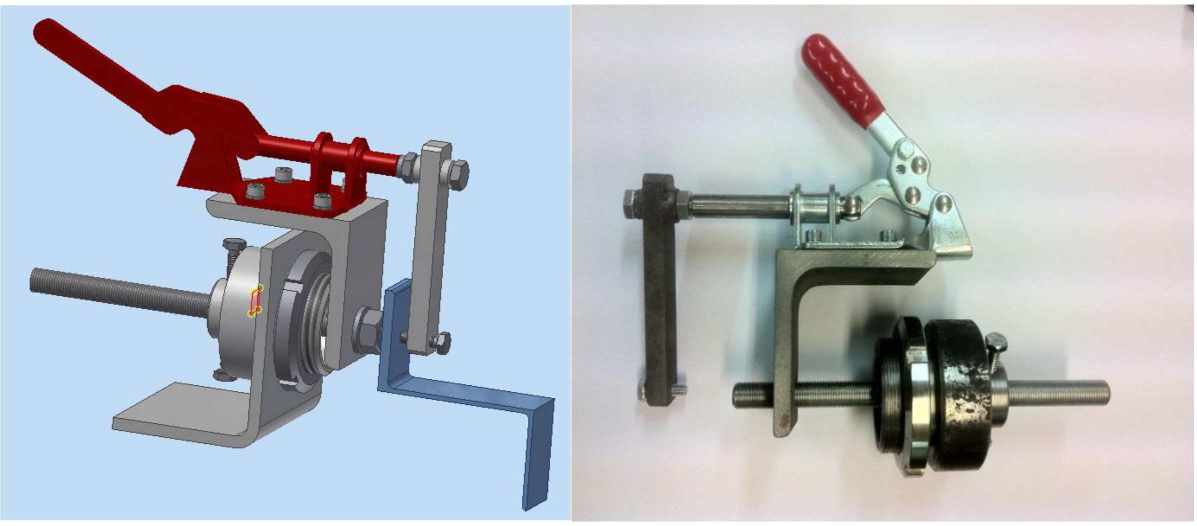


Figure 6.1. Designed panel leveling tooling on the left in closed position and fabricated assembly on the right in opened position

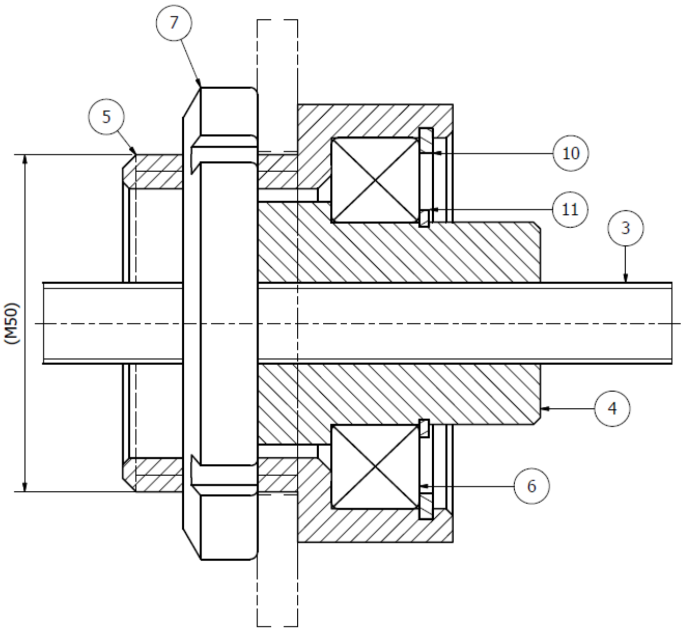


Figure 6.2. Bearing housing and fastening approach

Designed tooling was fabricated and testing was done. During the testing of designed tooling problems were found out. The rigidity of the structure was not enough. It means that the rotation of the nut to certain angle doesn't make the linear movement on a desired length because of the structure deformations. Also the backlash of the bearing reduces the stability and increases the deviations.

6.2. Pneumatic fastening and leveling tooling

The new fastening and leveling tooling was proposed because of the unsuccessful design of previously made tooling. In a purpose to increase the setup speed there is an idea to use pneumatic cylinders for the panel clamping. Linear/swivel clamp available at market is the acceptable mounting problem solution. The linear/swivel clamp is used for all types of clamping. Through the combination of the linear and swivel motion of the piston rod, it is possible to insert and remove work pieces even beyond the clamping range. It is possible to choose between versions swiveling to the right or to the left. Measured panel has Z-section as the basement. Using swiveling cylinder will facilitate panel mounting/demounting from the frame. Figure 6.3 illustrates proposed design of the fastening and leveling.

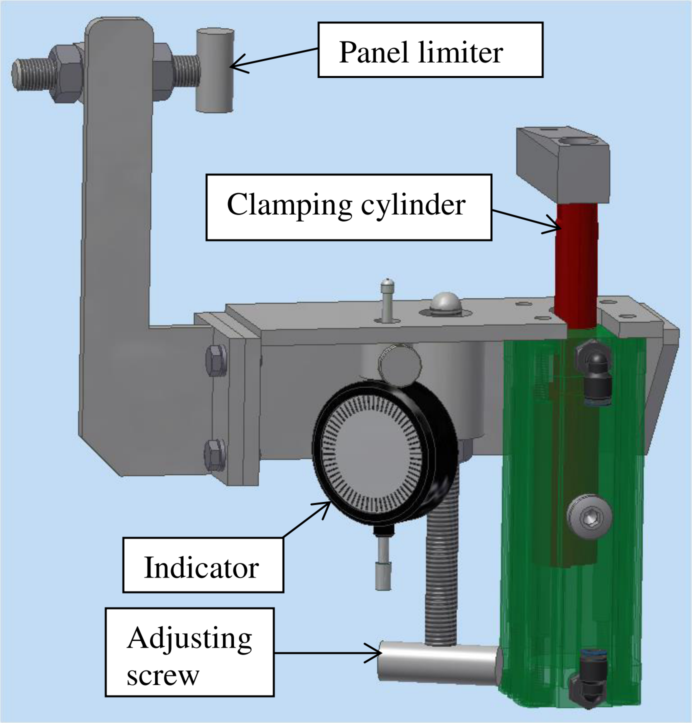


Figure 6.3. Pneumatic fastening and leveling tooling

To the main body of the fastening and leveling tool are attached working elements. Measured panel is located by the zero point directly to the adjusting screw tip. Clamping cylinder in closed position force panel against adjusting screw. Panel leveling is possible by adjusting screw rotation and clamping cylinder linear stroke correspondent vertical movement. Also there is implemented panel limiter which main purpose is to simplify measured panel installation into the correct position.

Market research and quotation showed that the most convenient choice for the cylinder is linear/swivel clamp CLR by Festo [9]. Specifically was selected cylinder CLR 32-20. The piston diameter d of the given cylinder is 32 mm and stroke equals to 20 mm what should be enough for clamping. Theoretical force F at 4 bar pressure P can be calculated using following formula:

$$F = P \cdot \frac{\pi \cdot d^2}{4} = 0{,}4 \cdot \frac{\pi \cdot 32^2}{4} = 322\ N \tag{6.2}$$

The data gathered during the measuring practice showed that the optimal force for the panel clamping equals to 200 N. Effective clamping force is enough to hold panel in stable position.

The maximum zero points quantity for one reflector panel is 7 as it is shown in chapter 3. Respectively the quantity of fastening and leveling assemblies equals to 7.

In order to use pneumatic cylinder, pneumatic system has to be done. There is a constant compressed air supply possibility in the measuring room, fed by the manufacturing main piping.

There is a need to regulate the air pressure for clamping cylinders aimed to have a possibility to change cylinder clamping force. Also air preparation is obligatory as well. For these purposes can be used filter regulator unit (Figure 6.4.). With this device, the filter and pressure regulator are combined into a single unit. The sintered filter with water separator removes contamination, pipe sinter, rust and condensate from the compressed air.

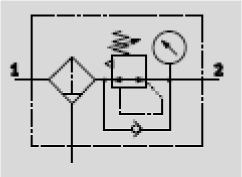


Figure 6.4. Filter regulator

Figure 6.5. Filter regulator MS4-LFR-1/4-D7-ERM-AS

As the filter regulator unit MS4-LFR-1/4-D7-ERM-AS supplied by Festo was selected (Figure 6.5.) [10].

It was decided to use direct type of control valve to operate the cylinders. When panel is installed to the measuring frame, operator has to turn valve to the open position and cylinders will clamp the panel. The valve function is 4/3-way, closed or exhausted. When the cylinders are closed the valve can be switched to the middle position. When the measurements are performed valve has to be set to the closed position and cylinder will release the panel. Finally rotary slide valve Festo VHER-BH-M04C-M05-UD was chosen [11].

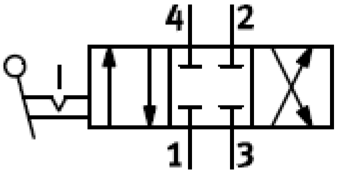


Figure 6.6. Hand lever valve

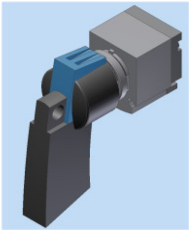


Figure 6.7. Valve VHER-BH-M04C-M05-UD by Festo

Working principle of designed pneumatic system is shown on the scheme below.

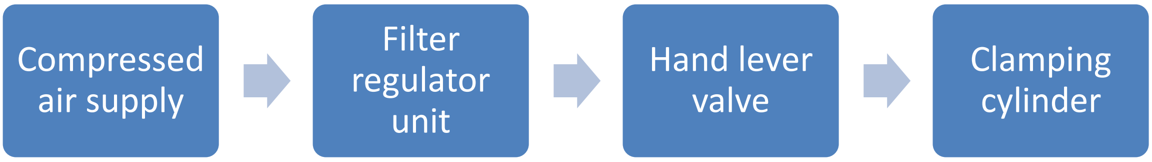


Figure 6.8. Working principle

Final pneumatic scheme is attached in the appendix of this thesis.

7. DRIVES SELECTION

The purpose of the drives for measuring system is to rotate needed load. First drive has to rotate cantilever for 30 degrees with accuracy in one degree. The second drive should rotate the camera on 90 degrees with a lower accuracy equaled to 2-3 degrees. For the both cases this is positioning drive.

This positioning task can be solved using open-loop or closed-loop control. For this purpose servomotors and stepper motors can be outlined.

Servomotors are especially designed and built for use in feedback control systems. This requires a high speed of response, which servomotors achieve by having low rotor inertia. Servomotors are therefore smaller in diameter and longer than AC and DC motor form factors. They must often operate at low zero speed, which makes them typically larger than conventional motors with a similar power rating. Within a specific power range, different inertias may also be specified. They are used in a wide variety of industrial applications, such as robots, machine tools, positioning systems, and process control.

Servomotors are driven by servo drives that provide precise velocity, torque, and position control by using encoder, resolver, and/or current signals that comprise the feedback components of a servomechanism [12].

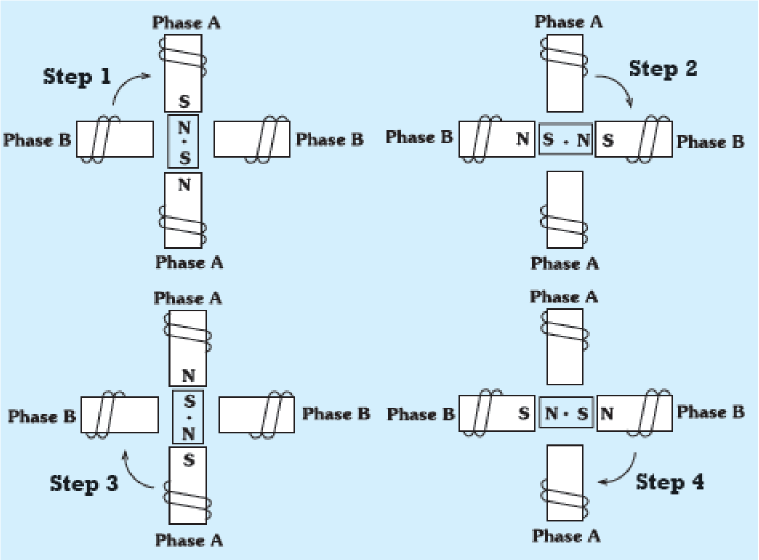


Figure 7.1. “One Phase On” stepping sequence for two phase motor [13]

A stepper motor is a DC motor that rotates a specific number of degrees based on its construction, that is, number of poles. It converts digital pulse inputs to shaft rotation; a train

]

of pulses is made to turn the motor shaft by steps. This allows the position to be controlled precisely without a feedback mechanism. Typical resolutions of commercially available stepper motors range from a few steps per revolution to as many 400. They can follow signals of up to 1200 pulses per second and may be rated up to several kW [14].

Figure 7.1 illustrates a typical step sequence for a simplified 2 phase motor. In step 1, phase A of the 2 phase stator is energized. This magnetically locks the rotor in the position shown, since unlike poles attract. When phase A is turned off and phase B is turned on, the rotor moves 90 degrees clockwise. In step 3, phase B is turned off and phase A is turned on but with the polarity reversed from step 1.This causes another 90 degrees rotation. In step 4, phase A is turned off and phase B is turned on, with polarity reversed from step 2. Repeating this sequence causes the rotor to move clockwise in 90 degrees steps [13].

Though steppers can be a lower-cost alternative to servos for positioning applications since feedback is not required, stepper motors do not provide nearly as much torque as servomotors, especially at higher speeds.

For given application stepper motors would be a perfect choice as a cost reduction component. Stepper motor features allow refusing from closed-loop control system. Also in stepper motor choice favor can be mentioned high motor torque on the low revolution speed what is desirable for given system.

7.1. Drive of the cantilever

Selecting the proper motor and driver to meet a specific application needs motor torque calculation. Generally speaking, it is needed to follow the below steps to choose the proper motor and driver.

- Determine the motion profile and calculate acceleration, deceleration and maximum velocity required to make the desired move.
- Calculated inertia, friction and load torque using necessary formulas.
- Determine required motor torque for the specific application.
- Select proper motor and driver based on their speed-torque characteristics.

7.1.1. Moment of inertia.

Moment of inertia determines the torque needed for a desired angular acceleration about a rotational axis. To calculate the needed moment of inertia J_T for this rotating system inertia of the cantilever J_C and inertia of the camera J_L should be summarized:

$$J_T = J_C + J_L \tag{7.1}$$

We can assume that rotating structure consists of the rod of length L and mass m, rotating around one end and solid cylinder of radius r and mass M.

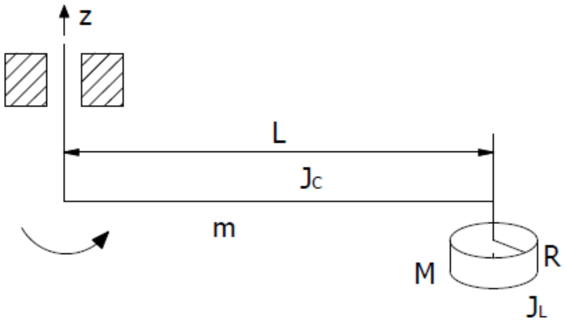


Figure 7.2. Rotating cantilever scheme

Cantilever could be evaluated like a rod of length L and mass m, rotating around one end. The moment of inertia for the rod is:

$$J_C = \frac{1}{3} \cdot m \cdot L^2 \tag{7.2}$$

where m – 4 kg,

L – 2 m.

Calculating the moment of inertia for the cantilever:

$$J_C = \frac{1}{3} \cdot 4 \cdot 2^2 = 5{,}3\ kg \cdot m^2 \tag{7.3}$$

The camera can be assumed as a solid cylinder of radius r and mass M. The moment of inertia for the cylinder is:

$$J_l = \frac{1}{2} \cdot M \cdot r^2 \tag{7.4}$$

where m – 6 kg,

r – 0,15 m.

Formula 7.4 is given for the cylinder which rotates around its center of gravity. But in our case the rotation axis locates at the end of the cantilever on the distance L. For this case the parallel axis theorem, also known as Huygens–Steiner theorem should be used:

$$J_L = J_l + M \cdot L^2 \tag{7.5}$$

Calculating the moment of inertia for the cantilever:

$$J_l = \frac{1}{2} \cdot 6 \cdot 0{,}15^2 = 0{,}07\ kg \cdot m^2 \tag{7.6}$$

$$J_L = 0{,}07 + 6 \cdot 2^2 = 24{,}07\ kg \cdot m^2 \tag{7.7}$$

Calculating the moment of inertia for the system:

$$J_T = 5{,}3 + 24{,}07 = 29{,}37\ kg \cdot m^2 \tag{7.8}$$

7.1.2. Torque calculation

Angular velocity ω of the cantilever was taken approximately equal to one revolution per minute or π/30 rad/s during the experiment described in chapter 5.7. This speed value has to provide stable rotation without vibration. Also higher velocity is undesirable because of “PRO-SPOT” heating problem. Too high frequency of shooting via “PRO-SPOT” projector can lead to the failure because of the light bulb overheating and fuse.

Needed torque can be calculated using next formula:

$$T_a = J_T \cdot a = J_T \cdot \frac{\omega_1 - \omega_0}{t} \tag{7.9}$$

where ω_1 – final velocity, rad/s

ω_0 – initial velocity, rad/s

t – time for velocity change, s

Time t for velocity change is taken equals to 1 s, what will provide smooth acceleration excluding dangerous influence on the camera activity.

Calculating the needed torque:

$$T_a = 29{,}37 \cdot \frac{\frac{\pi}{30} - 0}{1} = 3{,}07\ N \cdot m \tag{7.10}$$

The time of rotation on needed 30 degrees will be equal to 5 s according to a graph 7.2. below:

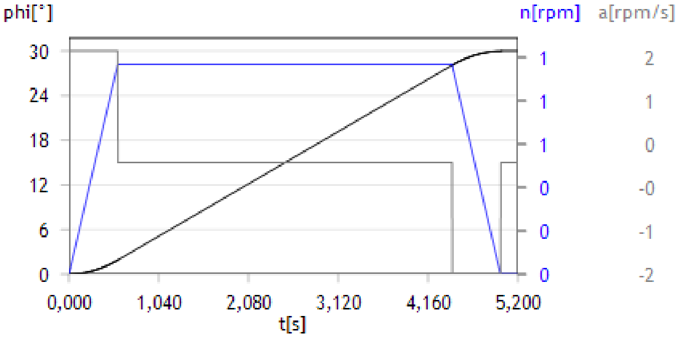


Figure 7.2. Motor diagram

7.1.3. Stepper motor selection

After local market search was found stepper motor which meets the requirements.

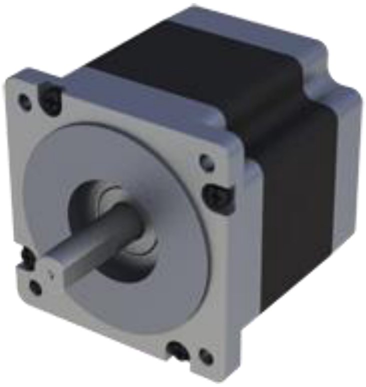


Figure 7.3. Stepper motor SM8680 [15]

Table 3.1. Stepper motor capabilities

Maximum holding torque, N·m	4,4
Maximum current per phase, A	4,2
Phase resistance, Ohm	0,8

Rotor inertia, $g \cdot cm^2$	1400
Weigh, kg	2,3
Phase inductance, mH	3,5

7.1.4. Gearbox necessity check

For the smooth working of the stepper motor one more factor has to be checked. The inertia ratio has to be equal or more than the value equals to 30 [16]:

$$Inertia\ ratio \geq= \frac{J_T}{J_0 \cdot i} \tag{7.11}$$

where J_T – load inertia,

J_0 – rotor inertia,

i – gear ratio.

Rotor inertia of the selected stepper motor equals to 1400 $g \cdot cm^2$. Calculated moment of inertia of designed structure equals to 29,37 $kg \cdot m^2$.

The needed gear ratio can be calculated using the previous formula:

$$i = \sqrt{\frac{J_T}{J_0 \cdot 30}} = \sqrt{\frac{29{,}37}{1{,}4 \cdot 10^{-4} \cdot 30}} = 83{,}6 \tag{7.12}$$

As the result it is necessary to include the reducer with the gear ratio equals to i=83,6.

7.1.5. Reduction gear selection

As it was found during the calculation there is a necessity of reducer inclusion to the system. There are several possible solutions of reduction implementation.

It can be achieved by using belt or chain transmission. On the assumption of calculated gear ratio equaled to 84 it is hardly achieved by named transmissions. Also these transmissions make the structure bulky. Another option is to use pinion-and-gear reducers. There are multiple types of them on the market: cylindrical, conical, worm, bevel, helical, shaft-mounted, planetary, etc.

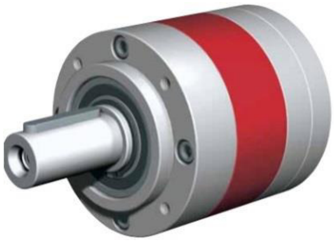


Figure 7.4. Selected planetary gear Planetroll [17]

Planetary gearing is often recognized as the compact alternative to standard pinion-and-gear reducers. Being suited for a wide range of applications – from electric screwdrivers to bulldozer power trains – these units are strong contenders when space and weight versus reduction and torque are chief concerns.

Finally was chosen planetary gear PD065-GAS100-1AA0 provided by Planetroll company. This gear series has advantages like high reliability, low backlash, high efficiency, long service life. Below are the capabilities of given gear. Gear interface was chosen according to the selected motor.

Table 5.1. List of gear capabilities

Capability	Value
Size	PD0065
Ratio	100
Number of gear stages	2
Nominal output torque T_{2n}, N·m	16
Max. permissible radial load, N	930
Max. permissible axial load, N	1080
Rated input speed, min^{-1}	3000
Service life, h	20000
Torsional backlash, arcmin	15

7.1.6. Final rotating cantilever design

After selecting all needed components the final design was made. Following figure demonstrates 3-dimensional model made in Inventor Autodesk software on the left and the section view on the right. The structure represents an axial assembly with rotating shaft in the center. To the bearing housing is mounted coupling housing in purpose of coupling assembly and lock nut tightening comfort. Planetary gearbox is mounted through the gear output flange to the coupling housing. Selected stepper motor is fixed directly to the planetary gear.

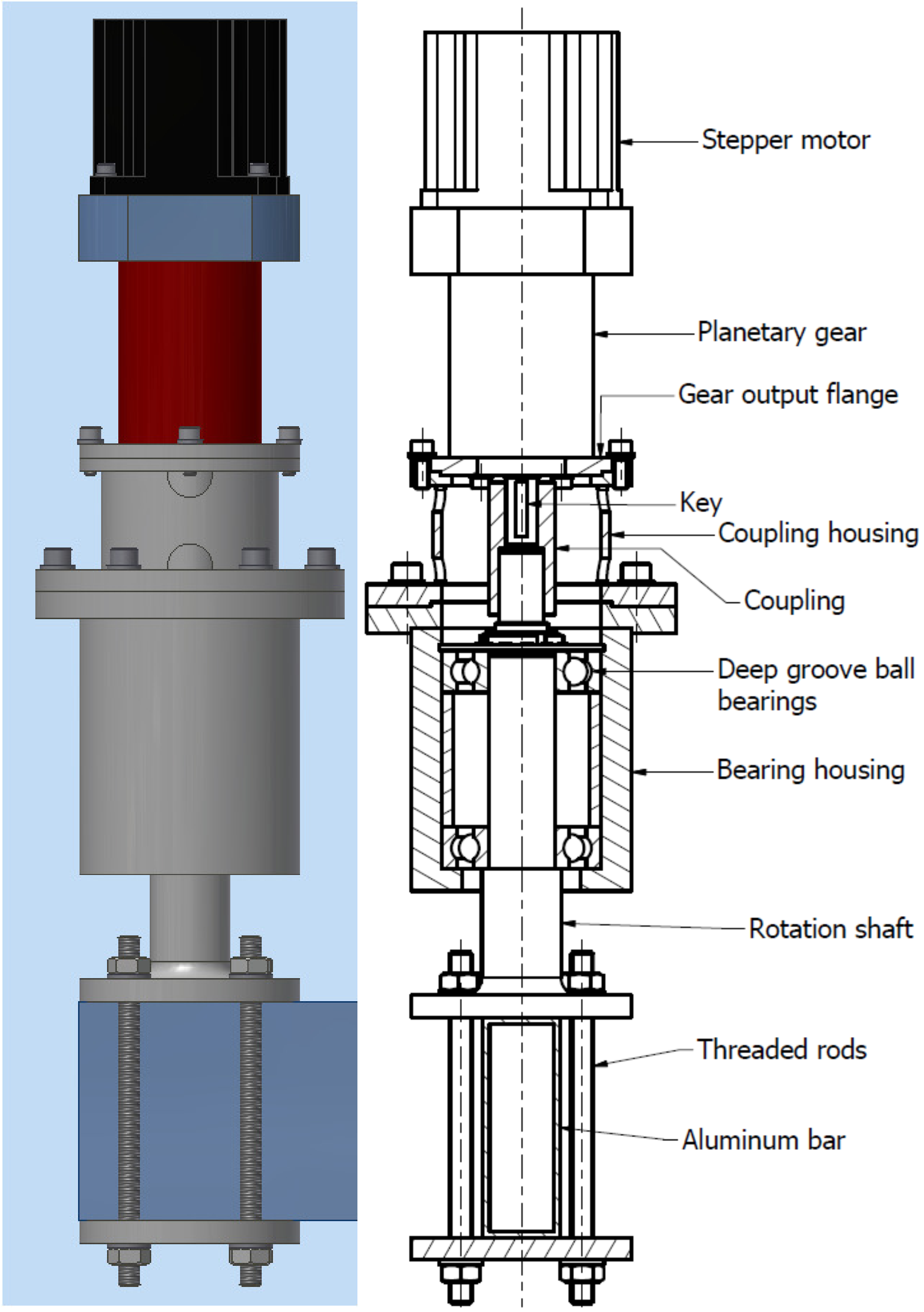


Figure 7.5. Rotating cantilever design

7.2. Drive of the camera calibration

Using the same principals of drive selection like it was done previously the calibration drive can be selected.

Photogrammetry camera can be assumed as solid cuboid with dimensions 222 x 134 x 120 mm. The weight of the camera equals to 4 kg. Inertia of camera can be evaluated using the formula of inertia moment for the solid cuboid:

$$I_C = \frac{m}{12} \cdot (w^2 + d^2) = \frac{4}{12} \cdot (0{,}222^2 + 0{,}134^2) = 0{,}01\ kg \cdot m^2 \tag{7.13}$$

Time t for velocity change can be taken as t=0,1 s.

Finally the needed acceleration torque can be calculated:

$$T_a = 0{,}01 \cdot \frac{\frac{\pi}{30} - 0}{0{,}1} = 0{,}01\ N \cdot m \tag{7.14}$$

Obtained value is very small and can be not considered.

Camera center of gravity with a turning bracket is displaced on l=50 mm. Static torque for this assembly is:

$$T_S = \frac{1}{2} \cdot l \cdot m = \frac{1}{2} \cdot 0{,}05 \cdot 4 \cdot 9{,}81 = 0{,}98\ N \cdot m \tag{7.14}$$

Assume to use the same stepper motor model as for the cantilever driver. The inertia ratio should be controlled further:

$$K = \frac{J_C}{J_0 \cdot i} = \frac{0{,}01}{1{,}4 \cdot 10^{-4}} = 71 \tag{7.15}$$

Inertia ratio shows the necessity of reducer use with gear ratio equals approximately to 2. At the same moment the gear demand can be neglected because of using the motor with much higher torque than it is needed and the lack of high precision of the rotation. For the camera calibration the same stepper motor SM8680 was selected.

7.2.1. Final camera calibration design

Below is represented the final design of camera calibration rotating assembly. The main bracket item 1 is a stepper motor item 5 base. The camera is attached to the bracket item 2 by rapid connection module. Bracket item 2 is fastened to the shaft item 3 by interference fit and fixed by a nut and spring washer. The shaft item 3 rotates on the deep groove ball bearing item 7 which is fixed in housing item 4. Bearing item 7 is settled down by the retaining ring item 8. Bearing housing item 4 is connected to the main bracket item 1. Coupling item 9 connects motor item 5 with a shaft item 3.

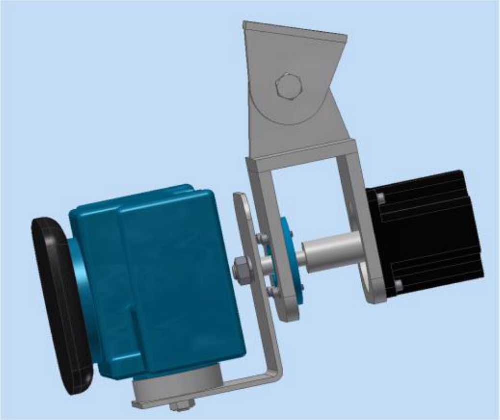


Figure 7.6. Three dimensional model of calibration drive

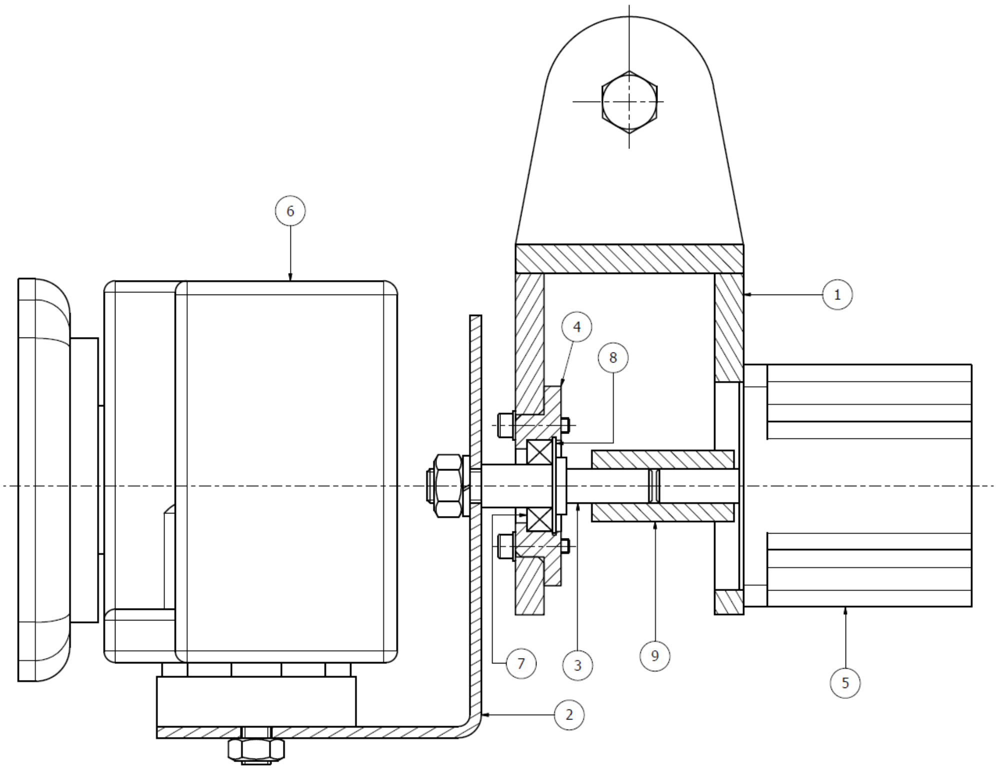


Figure 7.7. Section view of calibration drive

8. CONTROL

Previously in chapter 7 stepper motor was chosen as the driven element. There are two stepper motors in our system: Drive I for cantilever rotation and Drive II for camera calibration. The purpose of Drive I is to perform 30 degrees rotation forward or backward depending on system cycle. Drive II makes 90 degrees rotation of camera vertically when system is in the first state of cycle and horizontally to finish the cycle and to return the camera to starting position. Panel measuring cycle consists of two phases: forward phase and backward phase. The first phase starts by a photo shoot. Then Drive I performs 30 degrees rotation forward. This procedure is repeated 11 times. After that Drive II rotates camera on 90 degrees to vertical position. This is the start point of the second (backward) phase. The backward phase repeats all steps of forward phase but turning the cantilever to the opposite direction. After camera has made 11 shoots the backward phase is finished. During the full cycle camera makes 22 photo shoots, 11 forward rotations, 11 backward rotations and 2 orientation switches. The cycle ends by returning system into initial state, so the new measurement can be started. Cantilever never goes from last to the starting position, but returns by moving backward. This is foreseen in the safety reasons, to eliminate the possibility of wire damage. The full cycle is illustrated in process model scheme on figure 8.1.

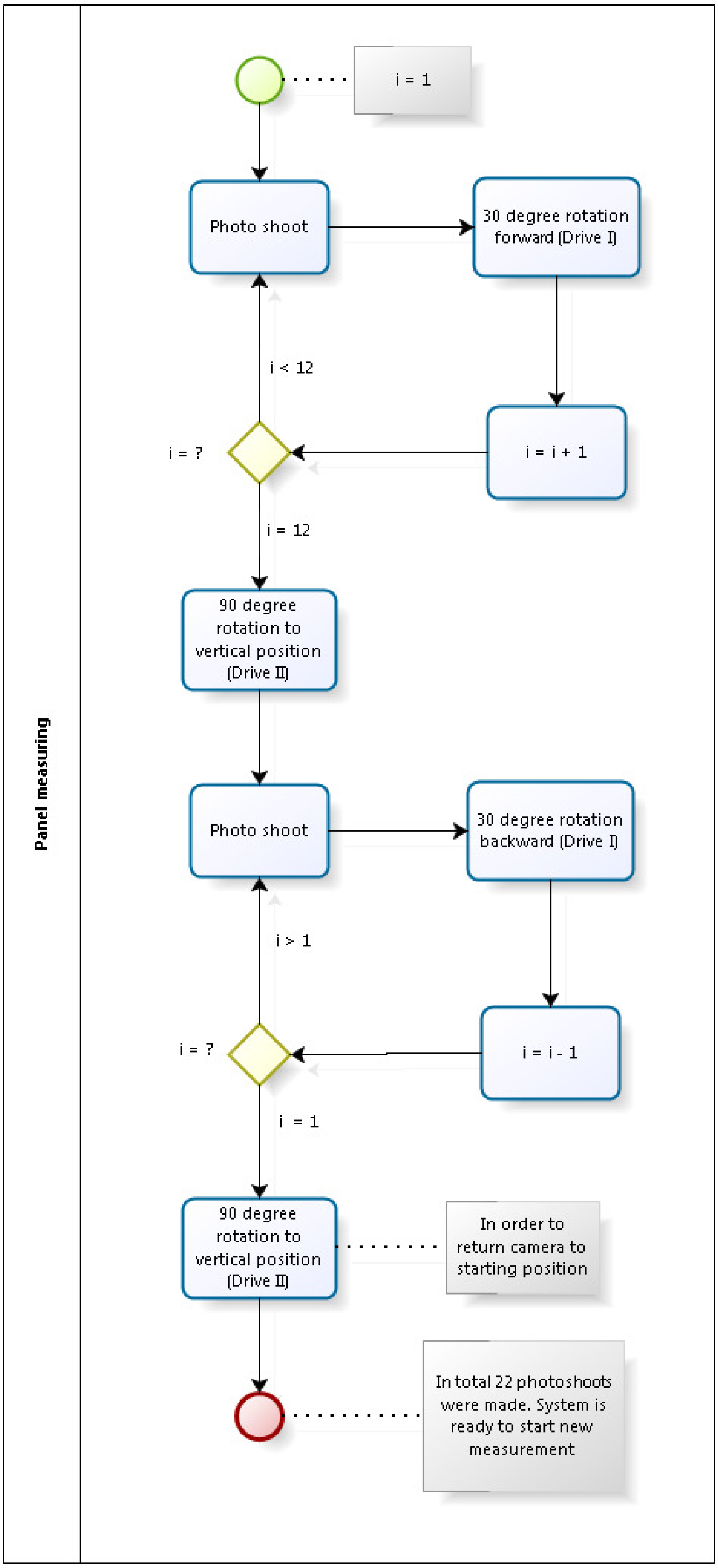


Figure 8.1. Measuring process

8.1. Control selection

In a closed-loop stepping motor system the rotor position is detected and fed back to the control unit. Each step command is issued only when the motor has responded satisfactorily to the previous command and so there is no possibility of the motor losing synchronism [4].

In an open-loop control scheme there is no feedback of load position to the controller and therefore it is imperative that the motor responds correctly to each excitation change. If the excitations changes too quickly the motor is unable to move the rotor to the new demanded position and consequently there is a permanent error in the actual load position compared to the position expected by the controller. A block diagram for a typical open-loop control system is shown in Figure 8.2 [14].

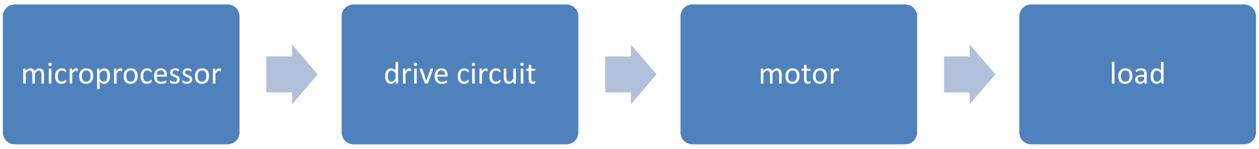


Figure 8.2. Microprocessor-based open-loop control

If the system has a high inertia, for example, the maximum stepping rate cannot be attained instantaneously; the stepping rate must be gradually increased towards the maximum value so that the motor has sufficient time to accelerate the load inertia [14]. In this case the all motor movements are always equal, changes only the direction of rotation. The load inertia doesn't change and the needed torque is the same as well. This allows settling the stepping rate to the right value by the experimental way. Drivers allow using microstepping. Microstepping is a way to divide steps of stepper motor to smaller parts, for example microstepping mode can be equal to - 1, 1/2, 1/4, 1/8, 1/16 of a step. Microstepping increases the smoothness of the movement and reduce vibration.

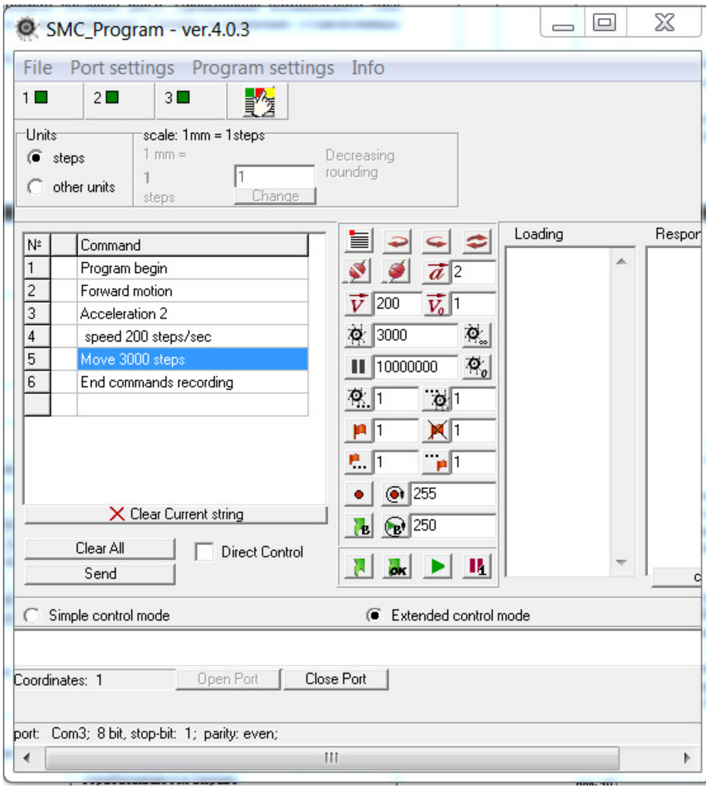
In order to choose between open and closed –loop approach the financial component was considered. As stepper motor features allow refusing from closed-loop control system, open loop will be chosen for given system.

8.2. Stepper motor driver

Stepper motors require drivers for operating. Both stepper motors always make equal movements on 30 degrees in case of Drive I and 90 degrees in case of Drive II. There is a programmable controller which performs as a driver as well. There is a possibility to program this controller to the needed acceleration, speed and rotation angle which meet problem demands. During the market research SMSD-4.2 controller was chosen.

Figure 8.3. Controller SMSD-4.2 [15]

Selected controller can be programmed using free software proposed by its distributer. Recording commands on controller goes by USB connection. Program composing goes in SMC-Program software. It is needed to set up rotation direction, acceleration, maximum speed and number of steps. Microstepping is possible as well, what is a main advantage when there is a need to reach a smooth movement with no vibration.



Units: ● steps ○ other units

scale: 1mm = 1steps

1 mm = 1 steps: 1

Nº		Command
1		Program begin
2		Forward motion
3		Acceleration 2
4		speed 200 steps/sec
5		Move 3000 steps
6		End commands recording

☐ Direct Control

○ Simple control mode ● Extended control mode

Coordinates: 1 Open Port Close Port

port: Com3; 8 bit, stop-bit: 1; parity: even;

Figure 8.4. SMC_Program software UI

8.3. Main controller

There are two drives in our system: Drive I and Drive II. Capabilities of the programmable controller with driver selected above are restricted, so the communication between them for the purpose of the process synchronization is impossible. Also there is a need to force camera to take a shoot. For these purposes system needs main controller, which will perform panel measuring process described on figure 8.5. This issue can be solved by microcontroller. In order to start the project with affordable investments there is a possibility to use the cheap microcontroller as an experimental variant for system efficiency verification. This solution will keep from extra expenses in case of some unexpected issues. Further simple microcontroller can be substituted by industrial PLC.

From the available on market microcontrollers there was selected Arduino UNO as the open-source, most suitable and handy. Arduino programming doesn't require additional costs and it was performed in the free software.

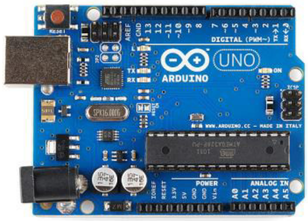


Figure 8.5. Arduino UNO microcontroller [18]

Communication between Arduino and SMSD-4.2 controller can be done reached by using relays for cycle processes. Photo shooting with photogrammetry camera is controlled by Arduino as well. Photogrammetry camera has trigger input which can be launched by relay as well.

9. PROJECT PRICE CALCULATION

Below is given the list of prices for the needed items.

Tabel 9.1. Total costs

Item	QTY	Price, EUR	Total price, EUR	Supplier
Stepper motor SM8680	2	132,3	264,6	Smart Motor Devices OÜ
Planetary gear PD065-GAS100-1AA0	1	286	286	OY MEKANEX AB Estonia
Stepper motor Driver SMSD-4.2	2	97,3	194,6	Smart Motor Devices OÜ
Pneumatic cylinders Festo CLR-32-20-L-P-A-B	7	194,5	1361,5	Festo Oy AB Estonia
Valve VHER-BH-M04C-M05-UD	1	28,5	28,5	Festo Oy AB Estonia
Filter regulator MS4-LFR-1/4-D7-ERM-AS	1	34,6	34,6	Festo Oy AB Estonia
Pneumatics components kit (fittings system, silencers,)	1	ca 50	50	Festo Oy AB Estonia
Arduino UNO	1	26	26	OÜ Dormikor
Mechanical parts kit (bearings, fasteners)	1	ca 50	50	Würth AS
Total			**2296**	

In this calculation material and fabrication costs are omitted, due to the possibility and permission to use materials from the facility reserves that will not cause additional expenses. In the built system would show successful results some additional costs are expected, for example Arduino controller has to be replaces with industrial PLC.

SUMMARY

The purpose of this thesis was to create the automated solution of making photogrammetric reflector panel measurements. The idea of measurements automation was found on the facility Vertex Estonia AS.

Measurement system has to provide RMS (root mean square) value of the reflector panel mirror surface. Measured panels are used on 9 and 13 meters parabolic antennas working on the Ka band of the electromagnetic spectrum. Measurements have to be performed by photogrammetry system provided by Geodetic Systems. The main tasks of this thesis were to find the possible solution to automate the process, choose appropriate drives and control system, make measurements more reliable, simplify panels gripping and “zero points” adjusting on the support frame prior to the RMS measurement.

In the first part of this paper the object of measurements (reflector panels) was described. The technical specification and the panel design were given. Also the manufacturing process was provided. Necessity of measurements and high precision demands were explained. There was entered a “zero points” concept and explanation.

The next chapter gives an overview of photogrammetry system, names its advantages and working principles. Description of the used photogrammetry system components “INCA 3a+” camera, retro-reflector targets, scale bar, coded targets, “PRO-SPOT” projector was made. Also there was explained panel leveling procedure that has to be done before measurements. The necessity of photogrammetry camera self-calibration was explained and resolved by 90 degrees rotation solution.

Third part consisted of overview of current measurement method. Step by step process was compiled. Operator actions are shown according to the tooled technology. The RMS value calculation method is shown.

The fourth topic of this thesis brings up a new measuring system concept that is based on the obtained practical photogrammetry experience. Possible solutions of measured object disposition were reviewed and the vertical variant was selected due to its outlined advantages. While choosing between possible options of photogrammetry camera manipulation — rotating cantilever approach was picked out. According to the photogrammetry fundamental principle there was defined disposition of measured object, photogrammetry camera and “PRO-SPOT” projector using graphical method. Base frame with supports for the measured

panel were designed. Finally it was brought a three dimensional model of the measuring system concept with two drives.

Fifth part consisted of the rotating cantilever design. The cantilever section was chosen according to the high rigidity demands with a low weight and performed by aluminum rectangular tube. It was proposed a shaft structure rotating on two radial bearings. Bearings reactions were calculated and suitable deep groove ball bearings were selected. Shaft check calculations were performed. Also there was proposed a design of camera calibration rotation assembly. In order to check the theoretical model of measuring via cantilever a test plant was built and tests were done. The possibility of proposed method was proved.

Sixth chapter consisted of new panel clamping and adjusting device design. Firstly designed and fabricated mechanism with a toggle clamps was declined due to the unsatisfactory test result. New design with pneumatic clamping cylinders was proposed. Pneumatic components were chosen and pneumatic scheme was made.

Next part describes the selection of drives. Stepper motors are chosen in a purpose of project cost reduction. Needed torque of motors was selected by calculating moment of inertia of the system and angular acceleration. For the both drives stepper motor SM8680 with a torque equaled to 4,4 N·m was selected. Inertia ratio check showed the necessity of gear usage for the cantilever drive. Planetary gear PD065-GAS100-1AA0 was chosen with a gear ratio 100. Final designs of cantilever and calibration drives were shown and described.

In the control chapter flow process of measuring was compiled and described. An open-loop control scheme was taken as a base. During the driver selection programmable controller SMSD-4.2 with a driver capability was chosen. Arduino UNO was used with a purpose of the process synchronization.

Final chapter gave an overview of main costs of proposed system design.

The overall purpose of this thesis was accomplished. The solution of measuring process automation was offered. Reflector panel measuring was made more reliable and the repeatability of measuring was increased by reducing human factor influence in the process. Proposed process made measuring faster. Simplification of panel mounting by pneumatics and “zero points” adjustment made work process less labor-consuming and routine.

KOKKUVÕTE

Lõputöö eesmärk oli luua automatiseeritud lahendus reflektor paneelide mõõtmiseks fotogramm-meetriga. Idee mõõtmise automatiseerimiseks sündis Vertex Estonia AS-is.

Mõõtesüsteem peab pakkuma reflektorpaneeli peegelpinna ruutkeskmise (RMS) väärtuse. Mõõdetavaid paneele kasutatakse 9 ja 13 meetrise läbimõõduga parabool-antennidel, mis töötavad elektromagnetilise spektri Ka lainealal. Mõõtmised teostatakse Geodetic Systems-i pakutava fotogramm-meetria süsteemiga. Antud lõputöö põhiülesanneteks oli leida võimalus protsessi automatiseerimiseks, valida sobivad ajamid ja kontrollsüsteemid, muuta mõõtetulemused usaldusväärsemaks, lihtsustada paneelide kinnitamine ja “nullpunktide” häälestamine mõõteraamil enne peegelpinna mõõtmist.

Töö esimeses osas kirjeldati mõõdetavat objekti (reflektor paneelid). Kirjeldati paneelide tehnilist disaini ja spetsifikatsiooni ning tootmisprotsessi. Selgitati mõõtmiste vajalikkust ja kõrgeid täpsuse nõudeid. Toodi sisse “nullpunktide” mõiste ja selgitus.

Järgmises peatükis antakse ülevaade fotogramm-meetria süsteemist, nimetatakse selle eelised ja tööprintsiibid. Tehti kirjeldus fotogramm-meetria süsteemi komponentide “INCA 3a+” kaamera, sihtmärkide, kalibreeritud sihtmärkide kogumite, skalaarlaudade, “PRO-SPOT” projektori kohta. Anti ülevaade paneeli paigutusprotseduurist, mis tuleb teostada enne mõõtmist. Selgitati ka Fotogramm-meetria kaamera isekalibreerimise tähtsust.

Kolmas osa koosnes praeguste mõõtmismeetodite ülevaatest. Protsessi kirjeldati samm-sammult kulgeva juhendiga ning operaatori käike näidati vastavalt häälestatud tehnoloogiale. Kirjeldati RMS väärtuse arvutamise meetodeid.

Neljandas peatükis toodi välja uue mõõtmissüsteemi kontseptsioon, mis baseerub omandatud fotogramm-meetria kogemustel. Vaadati üle võimalikud lahendused mõõdetava objekti paigutusest ning valiti vertikaalne paigutus, kuna sellel olid suurimad eelised. Kui valiti võimalike võimaluste vahel, kuidas konstrueerida fotogramm-meetria kaamera manipulaator, valiti välja pöörleva poomi struktuur. Kasutades graafilist meetodit määrati fotogramm-meetria kaamera ja “PRO-SPOT” projektori paigutus mõõdetava objekti suhtes vastavalt fotogramm-meetria töö põhiprintsiipidele. Mõõdetavale paneelile konstrueeriti alusraam koos tugedega ja lõpuks koostati kolmemõõtmeline mudel tervest mõõtesüsteemist koos kahe ajamiga.

Viies osa koosneb pöörleva poomi konstrueerimisest. Poomi profiil ja mõõtmed said valitud vastavalt suure jäikuse ning väikse kaalu nõuetele. Pakuti välja struktuur kahel radiaallaagril, arvutati välja laagrite reaktsioonid ja valiti sobivad radiaallaagrid. Lisaks tehti võlli kontroll-arvutused. Kirjeldati ka kaamera kalibreerimise pöörleva mehhanismi konstruktsiooni. Teoreetilise mudeli kontrollimiseks ehitati prototüüplahendus ja tehti katseid, mille käigus põhjendati selle mõõtmismeetodi kasutamine.

Kuuendas peatükis kirjedatakse uut paneeli kinnitus- ja häälestusmehhanismi disaini. Algselt disainitud mehhanism kiirkinnitusklambritega lükati tagasi, kuna testitulemused olid mitterahuldavad. Pakuti välja uus disain pneumaatiliste silindritega, millele vaililiti välja sobilikud komponendid ja koostati süsteemi skeem.

Töö järgmises osas kirjeldati ajamite valikut. Projekti kulude vähendamiseks valiti samm-mootorid ning vastavalt arvutatud inertsimomendile ja nurkkiirusele valiti vajalikud mootori pöördemomendid. Ajamite käitamiseks valiti samm-mootor SM8680, mille pöördemoment on 4,4 N·m. Inertsi suhte kontroll näitas ülekande kasutamise vajalikkust poomi ajamil – valiti planetaarreduktor PD065-GAS100-1AA0 ülekandearvuga 100. Näidati ja kirjeldati lõplikke poomi- ja kalibreerimismehhanismi lahendusi.

Süsteemi kontrolli peatükis koostati ja kirjeldati juhtimisprotsessi plokkdiagrammi. Baasiks valiti ilma tagasisideta kontrollmeetod ja valiti programmeeritav kontroller SMSD-4.2, millel on draiveri omadused. Protsessi sünkroniseerimiseks kasutati Arduino UNO arendusplaati.

Töö viimases peatükis antakse ülevaade süsteemi arendamise peamistest kuludest.

Lõputöö põhieesmärk sai täidetud. Pakuti välja mõõtmisprotsessi automaatiseerimise lahendus, mis muutis reflektorpaneelide mõõtmise usaldusväärsemaks ja parandas mõõtmiste korratavust vähendades inimfaktori mõju tervele protsessile. Välja pakutud lahendus tegi mõõtmised kiiremaks, samas kui paneelide pneumaatiline kinnitusmehhanism ja “nullpunktide” häälestamine tegid tööprotsessi vähem vaeva- ja aeganõudvaks.

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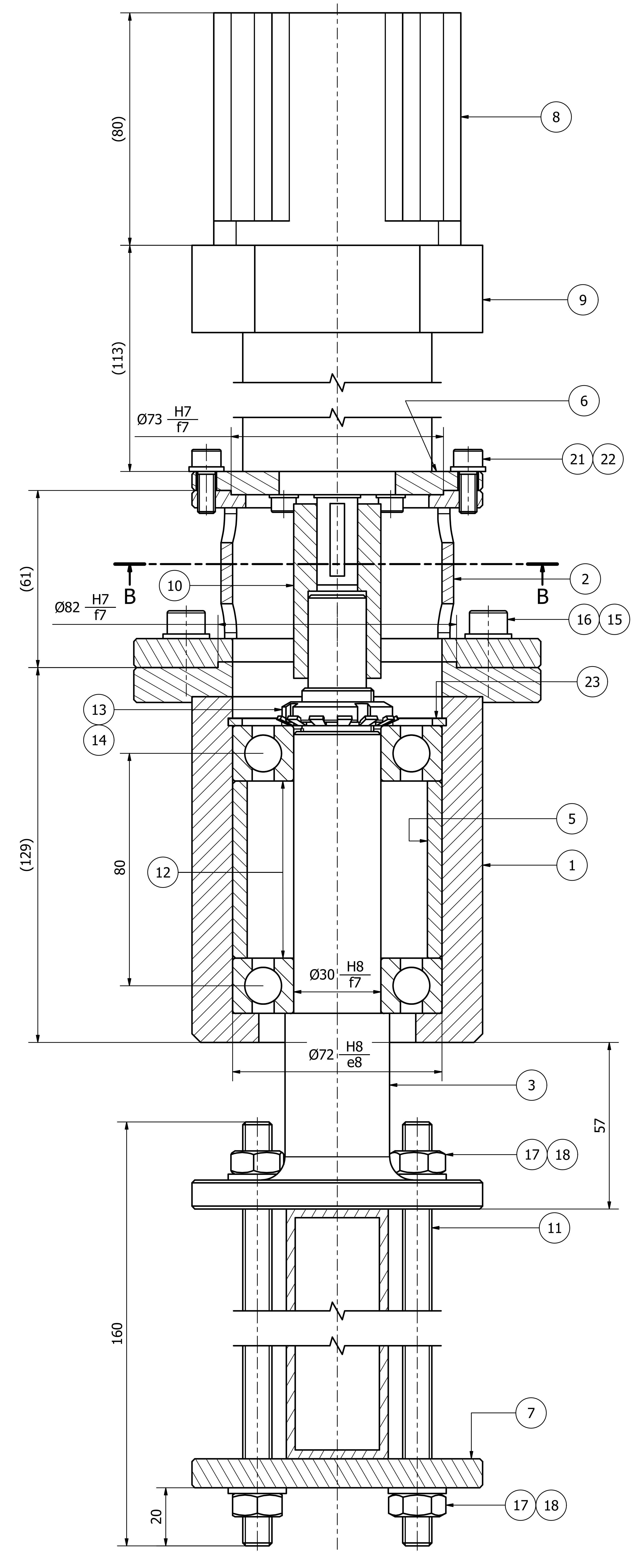
APPENDIX

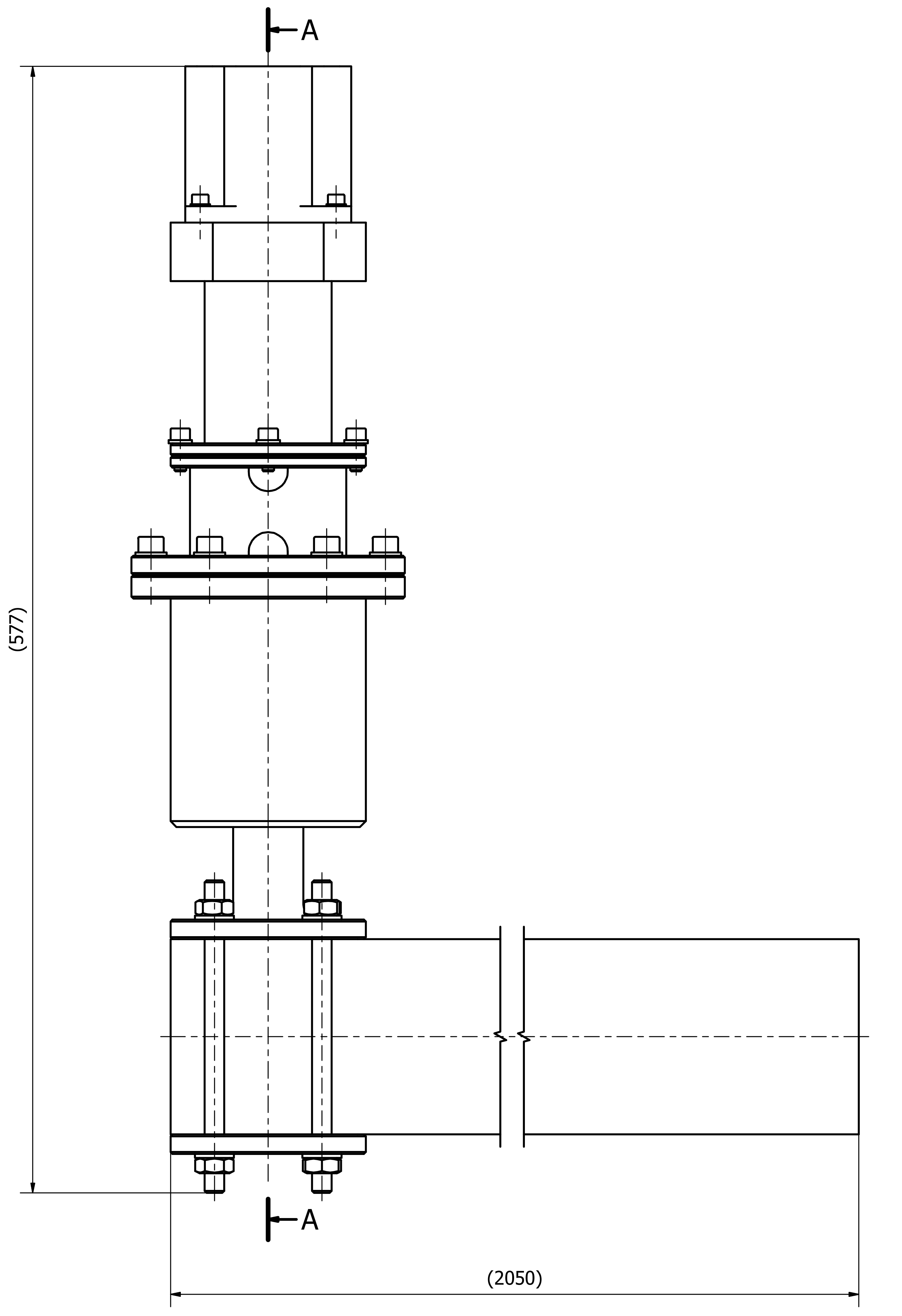
Appendix 1. Arduino code

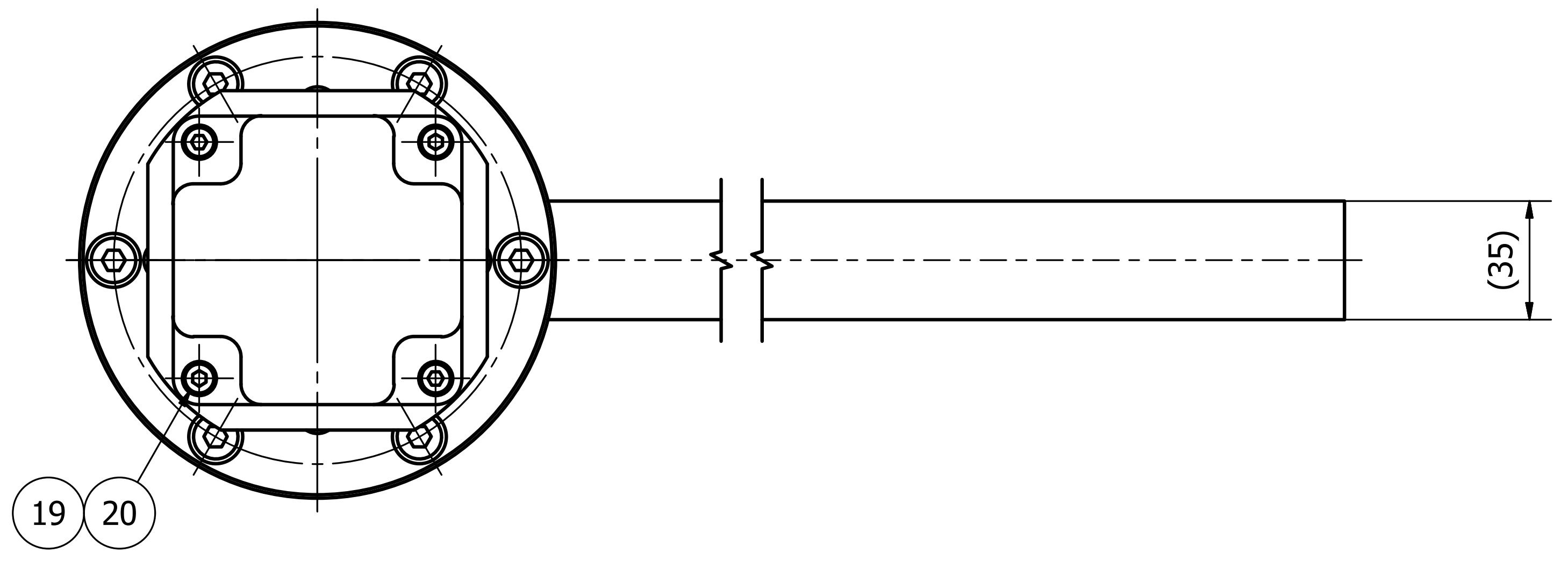
```
int switchPin = 6;
boolean lastButton = LOW;
boolean currentButton = LOW;
boolean sysOn = false;
int relay1 = 1;
int relay2 = 2;
int relay3 = 3;
int relay4 = 4;
int relay5 = 5;
int var = 0;

void setup() {
pinMode(switchPin, INPUT);          // input button to start the process
pinMode(relay1, OUTPUT);            // relay output for the photo shoot
pinMode(relay2, OUTPUT);            // relay output for the 30 degree rotation
pinMode(relay3, OUTPUT);            //relay output for the 90 degree rotation
pinMode(relay4, OUTPUT);            //relay output for the 30 degree rotation backward
pinMode(relay5, OUTPUT);            //relay output for the 90 degree rotation backward
}

boolean debounce(boolean last){
  boolean current = digitalRead(switchPin);
  if (last != current){
    delay(5);
    current = digitalRead(switchPin);
  }
  return current;
}

void loop() {                       // the loop function runs over and over again
  currentButton = debounce(lastButton);
    if(lastButton == LOW && currentButton == HIGH)
  {
    sysOn = !sysOn;
  }
  lastButton = currentButton;
  if(sysOn = HIGH){
  digitalWrite(relay1,HIGH);        // first photo shoot-start of the process
  delay(10);
  digitalWrite(relay1,LOW);
  delay(5000);
  digitalWrite(relay2,HIGH);        // first 30 degree rotation
  delay(10);
```

```
  digitalWrite(relay2,LOW);
  delay(60000);
  while(var < 11){                      //cycle for the 11 photo shoots
  digitalWrite(relay1,HIGH);
  delay(10);
  digitalWrite(relay1,LOW);
  delay(5000);
  digitalWrite(relay2,HIGH);
  delay(10);
  digitalWrite(relay2,LOW);
 var++;
   }
  digitalWrite(relay3,HIGH);            // camera calibration by 90 degree rotation
  delay(10);
  digitalWrite(relay3,LOW);
  delay(5000);
  digitalWrite(relay1,HIGH);
  delay(10);
  digitalWrite(relay1,LOW);
  delay(5000);
  digitalWrite(relay4,HIGH);            // start of the backward rotation
  delay(10);
  digitalWrite(relay4,LOW);
  delay(60000);
  while(var < 11){
  digitalWrite(relay1,HIGH);
  delay(10);
  digitalWrite(relay1,LOW);
  delay(5000);
  digitalWrite(relay4,HIGH);
  delay(10);
  digitalWrite(relay4,LOW);
 var++;
   }
digitalWrite(relay5,HIGH);              // camera 90 degree backward rotation
  delay(10);
  digitalWrite(relay5,LOW);

}

}
```

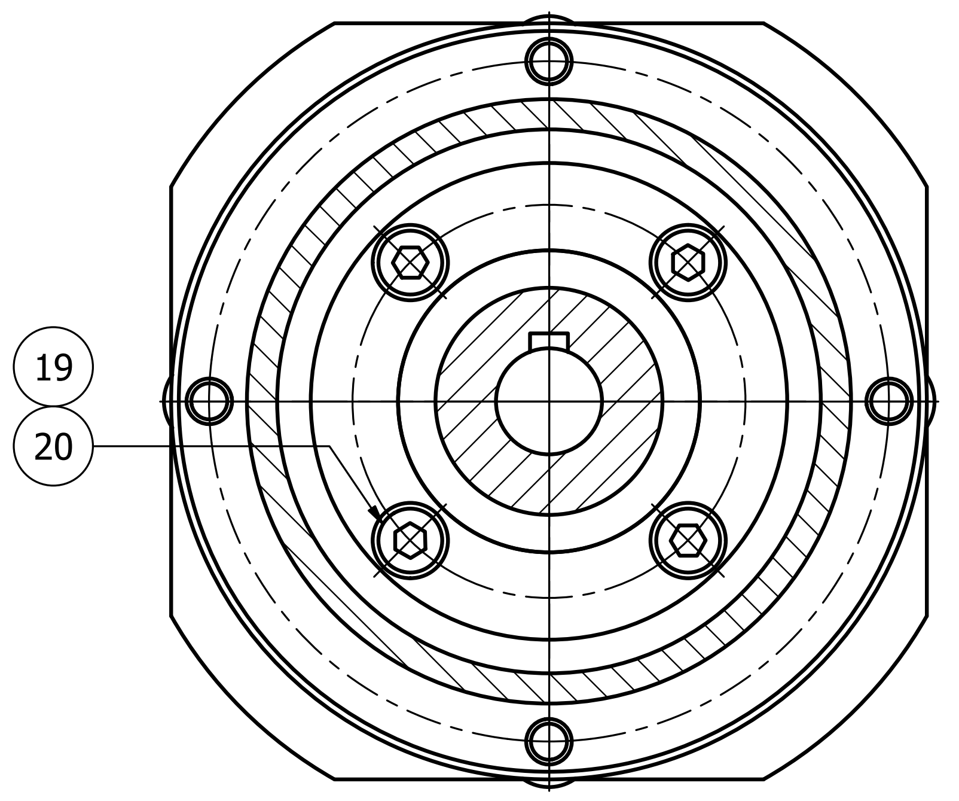
A-A (1 : 1)







B-B (1 : 1)



1. () Reference dimensions.
2. During the assembly grease the bearings.

23	1	DIN 472 - 72 x 2,5	Spring Retaining Ring		0.020	0.0		
22	4	DIN 125 - A 6,4	Washer		0.001	0.0		
21	4	DIN 912 - M6 x 16	Cylinder Head Cap Screw		0.007	0.0		
20	8	DIN 912 - M5 x 16	Cylinder Head Cap Screw		0.004	0.0		
19	8	DIN 125 - A 5,3	Washer		0.000	0.0		
18	8	DIN 125 - A 10,5	Washer		0.004	0.0		
17	8	DIN 934 - M10	Hex Nut		0.012	0.1		
16	6	DIN 912 - M8 x 20	Cylinder Head Cap Screw		0.015	0.1		
15	6	DIN 125 - A 8,4	Washer		0.002	0.0		
14	1	DIN 981 - MB5	Lockwasher		0.006	0.0		
13	1	DIN 981 - KM 5	Slotted Round Nuts		0.034	0.0		
12	2	DIN 625 SKF - SKF 6306	Single row ball bearings		0.325	0.6		
11	4	DIN 975 - M12 x 160	Threaded rod		0.098	0.4		
10	1	A16.07.00.03A	Coupling		0.220	0.2		
9	1	PD065-GAS100-1AA0	Planetary gear		1.600	1.6		
8	1	SM8680	Stepper motor		2.300	2.3		
7	1	A16.07.00.03A	Support		0.579	0.6	S235JR	
6	1	A16.07.00.03A	Gear flange		0.355	0.4	S235JR	
5	1	A16.07.00.03A	Distance bush		0.502	0.5	S235JR	
4	1	A16.07.00.03A	Tube		4.300	4.3	Aluminum	
3	1	A16.07.00.03A	Shaft		1.721	1.7	S235JR	
2	1	A16.07.02.00A	Coupling housing		1.353	1.4	S235JR	
1	1	A16.07.01.00A	Bearing housing		4.658	4.7	S235JR	
Item	Qty.	Drawing No.	Description	Form	Weight pe	Total Wei	Material	Note

					Kuuluvus		Tüki- arv
					Proj.N°	Koostu tähis	
Muud. Change	Arv Qty.	Leht Sheet	Allkiri Signat.	Kuup. Data			

TOLERANTSID TOLERANCES

Töödeldud pinnad Machined surfaces										
Mõõtmed Dim.	±	0,1	0,2	0,3	0,5	0,8	1,2	2,0	3,0	4,0
		3	6	30	120	315	1000	2000	4000	8000
	±	-	1,0	2,0	2,0	3,0	4,0	6,0	8,0	10

Keeviskonstruktsioonid, Gaasilõikus weldments

Konstr. Eng.	O.Movko		18.05.2016
Kontroll Contr.			
Kinnitas Confir.			

VERTEX
ESTONIA AS

Materjal Material

Mass
Weight
19,0 kg

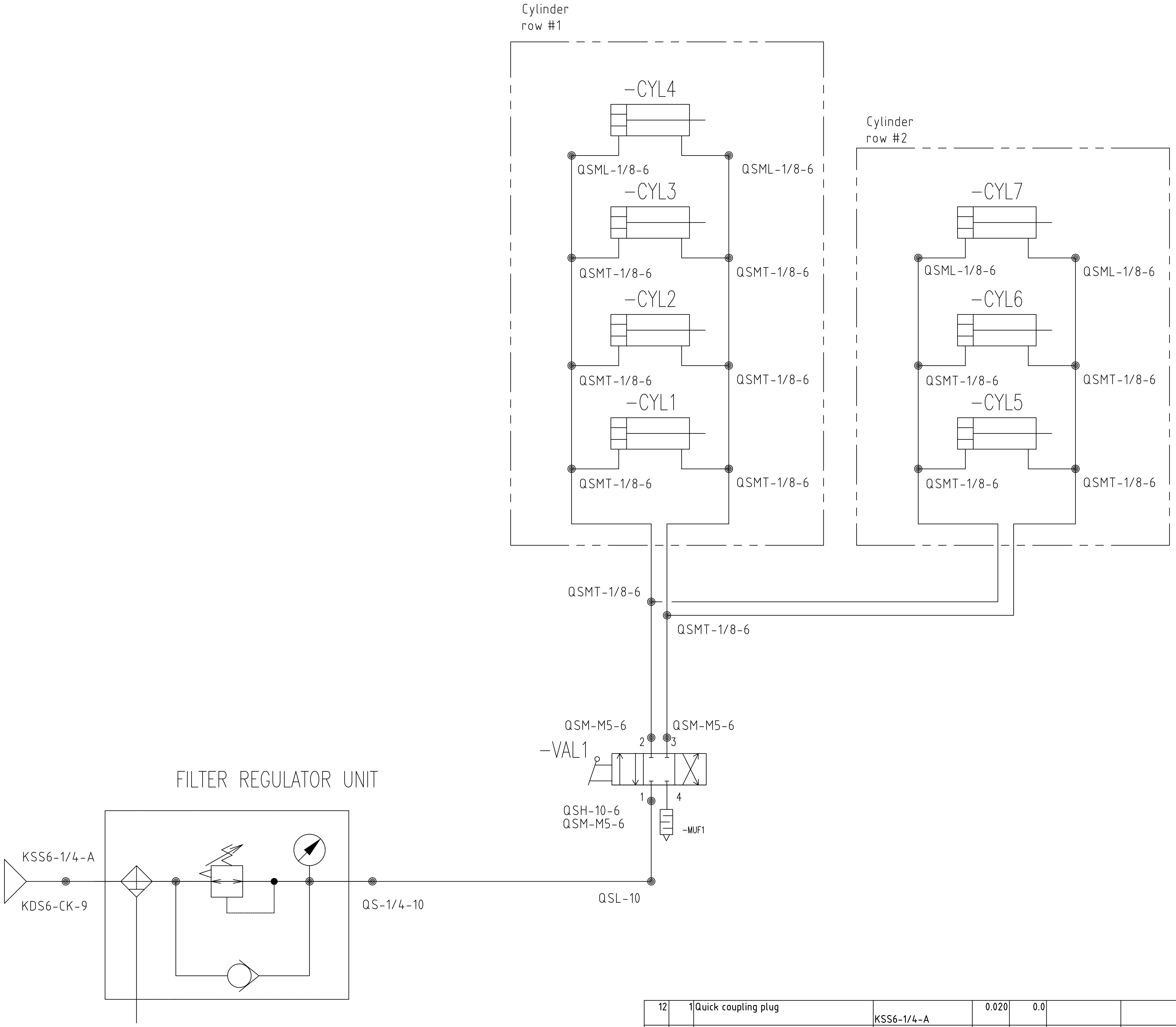
A16.07.00.00A

Mõõt
Scale
1:2

Leht 1 Sheet Lehti 1 Sheets

Rotating Cantilever Assembly

Automation of Photogrammetry System



Item	Qty.	Description (Size / Dimension)	Drawing No. (Standard / Note)	Weight per Item	Total Weight	Material	Note Order No.
12	1	Quick coupling plug	KSS6-1/4-A	0.020	0.0		
11	1	Push-in fitting	QS-1/4-10	0.020	0.0		
10	1	Quick coupling socket	KDS6-CK-9	0.104	0.1		
9	4	Push-in L connector	QSML-1/8-6	0.007	0.0		
8	12	Push-in T connector	QSMT-1/8-6	0.008	0.1		
7	3	Push-in fitting	QSM-M5-6	0.005	0.0		
6	1	Push-in sleeve	QSH-10-6	0.001	0.0		
5	1	Push-in L-connector	QSL-10	0.017	0.0		
4	1	Silencer	U-M5	0.001	0.0		
3	1	Hand lever valve	VHER-BH-M04C-M05-UD	0.080	0.1		
2	7	Pneumatic Cylinder	DSN-20-210-P	0.270	1.9		
1	1	Filter regulator unit	MS4-LFR-1_4-D7-ERM-AS	0.275	0.3		

Muud. Change	Arv Qty.	Leht Sheet	Allkiri Signat.	Kuup. Data	Proj.N°	Kuuluvus Koostu tähis	Tüki-arv

TOLERANTSID TOLERANCES

Töödeldud pinnad							Machined surfaces		
Mõõtmed Dim. ±	0,1	0,2	0,3	0,5	0,8	1,2	2,0	3,0	4,0
	3	6	30	120	315	1000	2000	4000	8000
±	-	1,0	2,0	2,0	3,0	4,0	6,0	8,0	10

Keeviskonstruktsioonid, Gaasilõikus weldments

VERTEX
ESTONIA AS

Konstr. Eng.	O.Movko		18.05.2016
Kontroll Contr.			
Kinnitas Confir.			

Materjal Material

Mass Weight

Automation of
Photogrammetry System

Mõõt Scale 1:1

Leht 1 Sheet Lehti 1 Sheets

Pneumatic scheme