DESIGN & IMPLEMENTATION OF A SCANNING PLATFORM FOR MOBILE ROBOTICS

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DESIGN & IMPLEMENTATION OF A SCANNING PLATFORM FOR MOBILE ROBOTICS

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ABSTRACT

DESIGN & IMPLEMENTATION OF A SCANNING PLATFORM FOR MOBILE ROBOTICS

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It is a great advantage of gaining knowledge about the environment for navigation. The environment should be measured during the employment as exactly as possible, in order to be able to react correctly. Robots are being used for different tasks at contaminated environments, places in danger or completely safe places. For robotic use, scanning capabilities of the environment are limited at the present. Adhering to the limitations of the scanning systems, the environment is scanned at a particular level and charted with appropriate software. In some cases, this scanning capability is not enough to react correctly.

Taking these needs into consideration, this thesis successfully demonstrates the design and implementation of a scanning platform for mobile robotics. A scanning platform with a laser rangefinder scanner will be addressed in a compact design with maximum field of view for quickly mapping and high resolution.

With this design, the scanning system will be provided by rotating laser rangefinder at z-axis in one dimension. Laser rangefinder will also measure the distance as the second dimension of the system. Also it rotates the laser beam at another axis which is different from the measuring distance axis and rotary z-axis. In this way, the scanning system will have the three-dimensional scanning ability. This design allows the scanning platform, continuous scanning capability at three dimensional.

Keywords: Laser Rangefinder, 3D Rangefinder, 3D Scanning

ÖZ

MOBIL ROBOTLAR İÇİN TARAMA PLATFORMUNUN TASARIMI VE UYGULAMASI

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Navigasyon için çevre hakkında bilgi sahibi olmak çok büyük bir avantajdır. Doğru tepki verebilmek için çevre hakkında edilen bilgi mümkün olduğunca görevlendirme sırasında olmalıdır. Robotlar kirli ortamlarda, tehlikeye yerlerde veya tamamen güvenli yerlerde farklı görevler için kullanılmaktadırlar. Robot kullanımı için, çevre tarama yetenekleri günümüzde oldukça sınırlıdır. Tarama sistemleri sınırlamalara bağlı kalarak, ortamı belirli bir düzeyde tarar ve uygun yazılım ile şekillendir. Bazı durumlarda, bu tarama kabiliyeti düzgün bir reaksiyon için yeterli değildir.

Bu tez, ihtiyaçları göz önüne alarak, mobil robotlar için bir tarama platformunun tasarım ve uygulamasını başarılı bir şekilde göstermektedir. Bir lazer mesafe ölçücü ile kompakt tasarımlı tarama platformu maksimum görüş açısı ile yüksek çözünürlükte hızlı haritalama için ele alınacaktır.

Bu tasarım ile lazer mesafe ölçücü z-ekseninde dönerek birinci boyutu sağlayacak, lazer mesafe bulucu ise sistemin ikinci boyutu için mesafe ölçümü yapacaktır. Ayrıca, mesafe bulucu lazer ışığını mesafe ölçüm ekseni ve dönen z-ekseninden farklı olarak başka bir eksende döndürmektedir. Bu şekilde, tarama sistemi, üç

boyutlu bir tarama yeteneğine sahip olacaktır. Bu tasarım, üç boyutlu olarak tarama platformuna, sürekli tarama kabiliyeti sağlayacaktır.

Anahtar Kelimeler: Laser mesafe bulucu, üç boyutlu mesafe bulucu, üç boyutlu tarama

To my family and my love;

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c	Speed of Light
t	Time
d	Distance
μm	Micro Meter
m	Meter
mm	Millimetre
º	Degree
msec	Millisecond
W	Watt
n/a	Not Applicable
V_{DC}	Volt DC
D	Dimensional
2D	Two Dimensional
3D	Three Dimensional
Nm	Newton Meter
kg	Kilogram
rad	Radian
DC	Direct Current
Ω	Ohm

ACRONYMS

rpm	Revolutions per minute
NA	Not Applicable
LRF	Laser Rangefinder
min	Minimum
ATV	All Terrain Vehicle
ROS	Robot Operating System
W	Weight
Wed	Weighted
S	Score
USB	Universal Serial Bus
CAD	Computer Aided Design
QTY	Quantity

CHAPTER 1

INTRODUCTION

1.1. Aim and Scope of the Study

Range sensors have been around for over thirty years. With the advancement of technology, these sensors have developed into compact systems that are deployed in many different situations. Manufacturing and robotics have both taken advantage of 3D sensing technology. Range sensors can help to achieve 3D mapping data by providing information about the area of interest. They provide real time information about selected area.

Autonomous robots have a wide range of potential applications including mobile mapping. For autonomous robots or inspection systems to perform correctly, the range sensors have to operate on a certain degree of accuracy and precision. The limit of how well these systems perform is directly related to how well the range sensors and their scanning mechanism perform. Therefore, the dependence on sensors and scanning mechanism is critical. Knowledge of how these sensors work and what are their limitations is a major concern for a particular application.

1.2. Motivation

In this thesis, it is aimed to develop a system that provides 3D captures of the environment with the help of a 2D laser rangefinder and a scanning platform. For this purpose, URG-04LX from Hokuyo manufacturer [10] is used in this thesis. For aim of this thesis, indoor 3D scanning has been selected for motivation. A further requirement of the system is to be easily located on other robot platforms. As an example, if higher measurement range is needed, the HOKUYO rangefinder can be replaced by higher performance laser rangefinder. It can be used at outdoor scanning at higher distances.

Object search is a critical ability for any robot whose task involves a 3D mapping. Cameras or 3D scanning mechanisms do not answer the needs of a search task and do not have a capability scanning at higher scanning field of views. Some of their mechanisms have ability of focusing but their scanning angle is very limited. Even if such a view is available, its resolution may not be sufficient for recognizing the target or path. Therefore, image with sufficient scanning angle and resolution is surely necessary.

Therefore, the scanning speed, resolution, ability of view selection and a higher scanning angle are the most important problems in the search task.

1.3. Objective of the Thesis

The main objective of the project that is described in this thesis, is to design of a scanning platform. This platform has to fulfill some objectives. These objectives can be summarized as:

- Scanning ability at 3D for indoor usage,
- Capability of higher rotation angle,
- Capability of changing scanning frequency, (scanning speed),
- Ability of selecting field of view,
- Designing a compact scanning platform,
- Ability of installing to various robot platforms.

With respect to these objectives, the important features of the system in question are:

- Mechanism of scanning platform,
- Selection of suitable components for;
    - Depth measurement,
    - Tilting or rotating measurement system,
    - Power transfer,
    - Data transfer,
- Design of construction,
- Assembly of scanning platform and rangefinder,
- Implementation of scanning platform and rangefinder,

1.4. Outline of the Thesis

Over the past decade, there has been a significant growth in scanning platforms research in the Literature. In this thesis, the rangefinder techniques are summarized and similar works in scanning mechanisms are examined with this summary and examination, the Literature survey of 3D range finding systems are reviewed.

In Chapter 2 and Chapter 3, the design of our scanning mechanism is discussed. Detailed descriptions of the system are presented. In the way of these descriptions, the results of first prototype are discussed. These descriptions and solutions provide the technical details required for 3D scanning mechanism.

In Chapter 4, implemented scanning platform is conducted with the result of real environment scanning plots.

In Chapter 5, the conclusions of the design are presented and the improvement to the prototype are discussed. Then, suggestions and future works are explained.

CHAPTER 2

LITERATURE REVIEW

2.1. Background

Mapping systems depend on range estimation techniques without any contact with interested area. Its quality based on lasers, their scanning mechanisms, and their scanning methods. By using different techniques of range measurement, it is possible to build laser range sensors with very different features applicable in many diverse application fields.

The most common form of laser rangefinder depends on the time of flight principle by sending a laser pulse in a narrow beam towards the object and measuring the time taken by the pulse to be reflected off the target and returned to the sender.

There are many types of rangefinders those have different applications. These applications can be categorized as three main domain; military applications, 3D modeling and industrial applications. The method of acquiring data changes with respect to its application.

Using a laser range finder with depth information is a common way to obtain 3D map of interested area. With commercial products, it is still too heavy, expensive and out of applicable scanning speed. In sections 2.3 Rangefinder Sensors and Comparison and 2.4 Reconstruction of a 2D Rangefinder for 3D Scanning, the review of different systems that can be used to design of a 3D scanning platform is made.

2.2. 3D Depth Measurement Using Time Flight Method

Rangefinders used for robotic applications, are direct measurement systems. These devices use two types of measurement method; triangulation method and time-of-flight method. There is taxonomy of measurement 3D imaging techniques which have been illustrated in Figure 2.1.

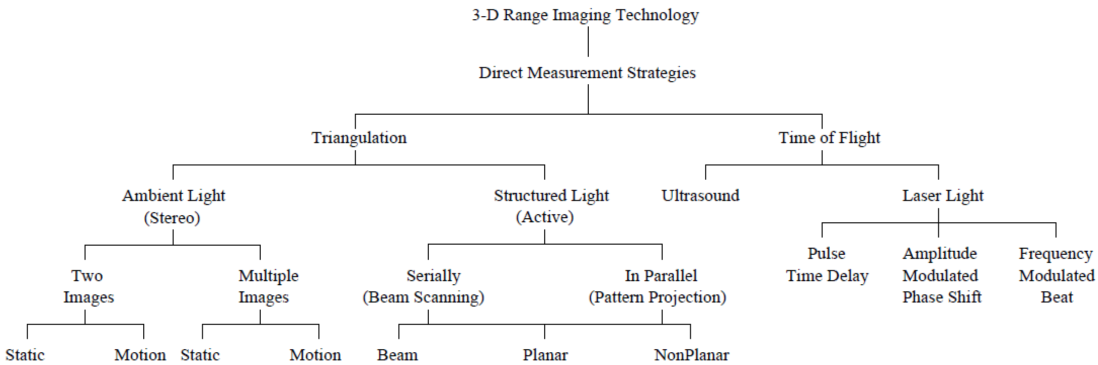

Figure 2.1: Techniques for measuring three-dimensional data [1]

An object distance can be determined by a laser rangefinder. It uses a laser beam for getting the correct distance to the object. Pulse time method, in other words, time of flight principle, is the most common form of laser rangefinder. Laser rangefinders have the capability of high-precision scanning abilities.

Time of flight laser rangefinders [2] rely on a simple principle. They function by measuring the time that a laser light takes to emanate out, reflect off a target and return to a receiver on the rangefinder.

Under the time of flight method, according to [3], "a laser range finder estimates the distance from a point (surface), by measuring the round trip time of a pulse of light. A laser (emitter) is used to emit a pulse of light and the amount of time before the reflected light is seen by a detector (receiver). Since the speed of light (c) is known the time (t) that a light pulse takes to arrive to the target and come back determinates the distance ($2d$); hence $c = 2d / t$ and therefore $d = c\ t / 2$. The advantage of time of flight range finders is that they are capable of operating very fast and over very long distances (up to many meters). This attribute makes them suitable for scanning large structures like buildings or geographic features."

2.3. Rangefinder Sensors and Comparison

There are many different techniques for measuring the distance by using a laser rangefinder. Determining scanning capability and its mechanism is linked with laser rangefinder's measuring technique. Therefore selecting a measurement technique is an important manner. Some other measurement techniques, especially time of flight technique are being used by commercialized devices, mentioned below.

Figure 2.2: AccuRange 4000 Laser Sensor [3]

According to [3], "The AccuRange 4000 laser rangefinder is Acuity's fastest sensor for measuring long distances. Employing time of flight measuring principles, the rangefinder can accurately gage distances up to 54 feet (16.45 m). Non-contact measurement is made simple with the three models within the AR4000 rangefinder series that have different laser diodes. The AR4000-LIR laser rangefinder has a working range to 54 feet (16.5m) on light surfaces (85% diffuse reflectance, such as paper or light paint) or 35 feet on a 30% reflectance target with an accuracy of 0.1 inches (2.5 mm). It uses an infrared 780 nm 8-milliwatt laser. This is the sensor of choice for best accuracy in most applications. The AR4000-LV rangefinder has a working range of zero to 40 feet (12.2 m) with an accuracy of 0.3 inches (7.5 mm). It uses a visible 670 nm 5-milliwatt laser. The AR4000-RET rangefinders are used with reflective tape supplied with the sensor. It is a low power, Class I eye-safe device, with an accuracy of 0.1 inches with a range of 2 to 54 feet. The LIR and LV models can be used in conjunction with the spinning mirror assembly and high speed interface card to make a laser line scanner for profiling scenes and objects."

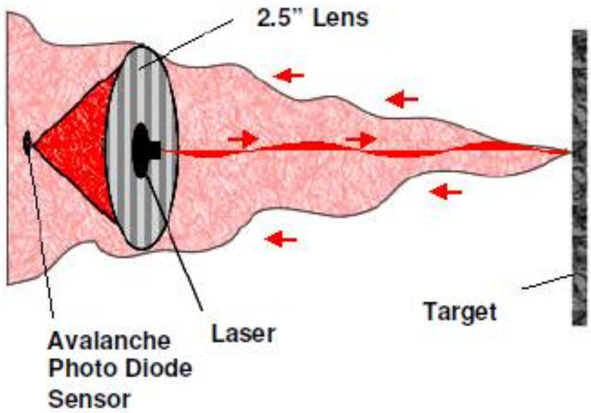

Figure 2.3: Working Principle of the AR4000 Rangefinder [4]

Because of the AR4000's concentric lens, it differs from other rangefinders. In Figure 2.3, functionality of AR4000 is shown. Laser light hits a target, after hitting, it returns to concentric lens. When the light is reflected, it is diffused. Concentric lens collects the diffused light and focuses on an avalance photodiode.

The AR4000 differs from other long-distance rangefinders in that the laser emitter and return signal collection lens are concentric. The illustration Figure 2.3 reveals the major functionality of the rangefinder. A collimated beam of laser light is emitted from a diode in the center of the collection lens. Light hits a target and is diffusely reflected, collected by the lens and focused on an avalance photodiode [4].

By this method, improved measurement accuracy and increased range can be succeeded. The returned energy is compared to a simultaneously generated reference that has been split off from the original signal, and the relative phase shift between the two is measured to ascertain the round-trip distance the wave has travelled. The phase shift expressed as a function of distance to the reflecting target surface is [5]:

$$\phi = \frac{4\pi d}{\lambda} \tag{2.1}$$

where ϕ is the phase shift, d is the distance value to target and λ is the modulation of wavelength.

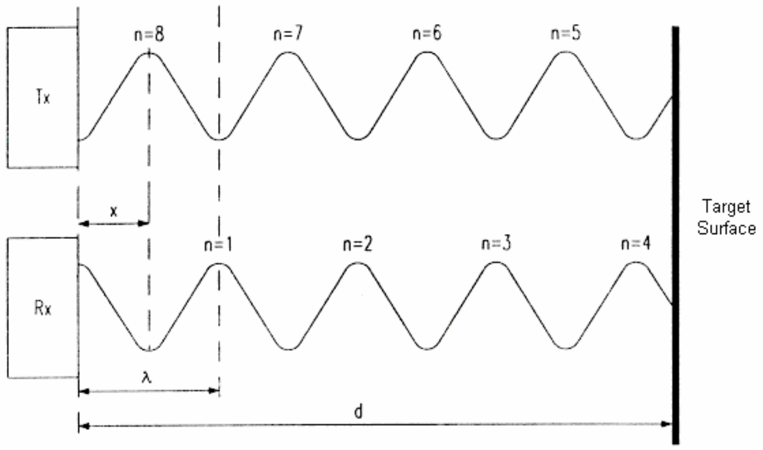

Figure 2.4: Relationship Between Outgoing and Reflected Waveforms [5]

In Figure 2.4, x is the distance corresponding to the differential phase ϕ. The desired distance to target *d* as a function of the measured phase shift ϕ is:

$$d = \frac{\lambda\phi}{4\pi} = \frac{c\phi}{4\pi f} \tag{2.2}$$

where c is the speed of light and f is the modulation frequency.

Figure 2.5: Sick LMS 200 [6]

This is one of the most famous laser rangefinder manufacturers in robotics (Figure 2.5). Manufacturer (Sick) has a wide variety of laser sensors either short range of wide range measurements for a wide variety of applications. Within their products, the most famous are the LMS 200 to 291 suitable for both outdoor and indoor measurements using the time of flight principle.

Figure 2.6: RIEGL Laser Measurement Systems [7]

Manufacturer (Riegl) applies time of flight principle in the totality of their laser products. Among their products, it is possible to find laser rangefinder (distance meters) which measure distance to a single point, industrial scanners or airborne scanners, which take information of one plane, and terrestrial scanners, which take

3D information about the environment. All of these products are able to take information over long distances (up to many meters) and some of them are even suitable for their use in aerial reconnaissance.

Figure 2.7: Zoller Fröhlich Laser Measurement Systems [8]

Zoller Fröhlich offers point measurement laser rangefinder able to measure up to 50 meters, applied in fast and exact range measuring for long term measuring of object (e.g. buildings) and ground movement. They also produce 2D laser rangefinder measurement systems applicable in the fields of infrastructure and landscape, for example the surveying of railways, tunnels, and streets. Finally, they also provide a 3D laser rangefinder, which has a wide range of applications alongside with software for the treatment of 3D information. Some of these applications are digital planning of factories and industrial facilities, architecture or virtual reality.

Figure 2.8: Micro-Epsilon Sensors [9]

Triangulation laser rangefinder, with accuracy of μ*m* and range up to cm are some of the products offered by Micro-Epsilon. As well, they offer some time of flight sensors up to 200m. Moreover, they offer a 2D/3D scanner based in triangulation principle as well, with measuring range z-axis up to 245 mm and measuring range x-axis up to 140 mm.

Figure 2.9: HOKUYO [10]

HOKUYO has a gamma of products called SOKUIKI sensors, which are 2D laser rangefinder with low power consumption, maximum range distance measurement of up to 4 meters, and scanning area (field-of-view) of 180º (PBS series) or 240º (URG series).

Table 2.1: Technical Characteristics of Different Laser Rangefinder Sensors

Manufacturer	**ACUITY-AccuRange**	**SICK**	**HOKUYO**	**MICRO-EPSILON**
Model	AR4000	LMS 200-30106	URG-04LX	Sensor LLT 2800-100
Price ($)	3800	5120	2280	1760
Measurement principle	Time of Flight	Time of Flight	Phase difference	Triangulation
Field of View	n/a	180°	240°	30°
Angular resolution	n/a	0.25°	0.36°	0.03°
Range Resolution	0.0125 mm	30 cm	10 mm	40 μm
Maximum range	16.5 m	80 m	4 m	0.3 m
Time taken for full scan	n/a	50msec	100msec	1msec
Points/scan	n/a	720	681	Up to 1024
Power consumption	2W+20W(@5V_{DC})	20W (@24V_{DC})	2.5W (@5V_{DC})	12W (@24V_{DC})
Data interface	RS-232/422	RS-232/422	RS-232, USB	RS-232/422, IEEE-1394
Weight and dimensions	140 x 64 x 64 mm; 1.6 kg	156 x 155 x 210 mm; 4.5 kg	50 x 50 x 70mm; 160 gr	(sensor)125 x 64 x 44 mm; 0.4 kg

The aforementioned manufacturers offer a wide product range of laser rangefinder that can be applied in different fields; from measurements in buildings or tunnels measurements to very accurate measurements of defects in small objects. Some of them offer solutions to acquire 3D point clouds alongside with the software required for the treatment of raw (optical) data. To make clear the differences between the different laser rangefinder devices, it has been compiled Table 2.1, which illustrates four major examples. These are 2D and spot laser rangefinders and have been chosen on the basis of fulfilling the desired features for their use in robotics, and consequently they would be used to solve the problem presented in this thesis. Although the laser rangefinder sensors provided in Table 2.1 are similar, they have very different features that make them more suitable for a specific application field.

The main difference between these four scanners is the measurement range: while the triangulation based laser rangefinder is able to measure up to 360 mm, the time of flight laser rangefinders reaches a maximum distance of 16 meters to 80 meters but they are differing at resolution point. To that respect, the HOKUYO sensor has a measurement range of up to 4 meters. It might be evident that the SICK and HOKUYO laser rangefinder offer similar features, but the SICK sensor is bigger and heavier but is able to take long-distance range measurements with the same accuracy as that of the HOKUYO sensor. Another major difference between these three laser rangefinder (Acuity, Sick and HOKUYO) is their applicability: the laser marking source can equally operate well outdoors but the HOKUYO can only operate indoors. The main advantages of the HOKUYO sensor are its wider field of view, low power consumption and the remarkably small size and weight.

2.4. Reconstruction of a 2D Rangefinder for 3D Scanning

Due to their high cost, large size, but long measurement range; commercial 3D laser range finders are still limited to their use in large scale projects aimed to the modeling of big structures, buildings, streets or even cities and land. They are useful for their application in urban environments, architecture, art, but most of them are not suitable with their scanning angle, high power consumption, scanning frequency and selecting field of view requirements in robotics applications field.

As an another solution, instead of using 3D scanners, which yield consistent 3D scans, some groups have attempted to build 3D volumetric representations of environments with several 2D laser range finders. 3D models are acquired just by moving the platform around and recording sensor data. [11], [12], [13]. There are some examples below for this kind of reconstructed sensors.

Figure 2.10: Research Vehicle Marge [11]

Recently it is becoming very popular in robotic laboratories the use of one laser scanner 2D with a mechanism to provide the third dimension. The most popular sensor used in this technique during the latest years have been the SICK LMS 200, (or in some cases SICK LMS 291, the only difference is the error, LMS 200 is more precise), since it offers a range of 80 meters, with an accuracy of 10mm. Moreover, SICK LMS 200 is suitable for outdoors use.

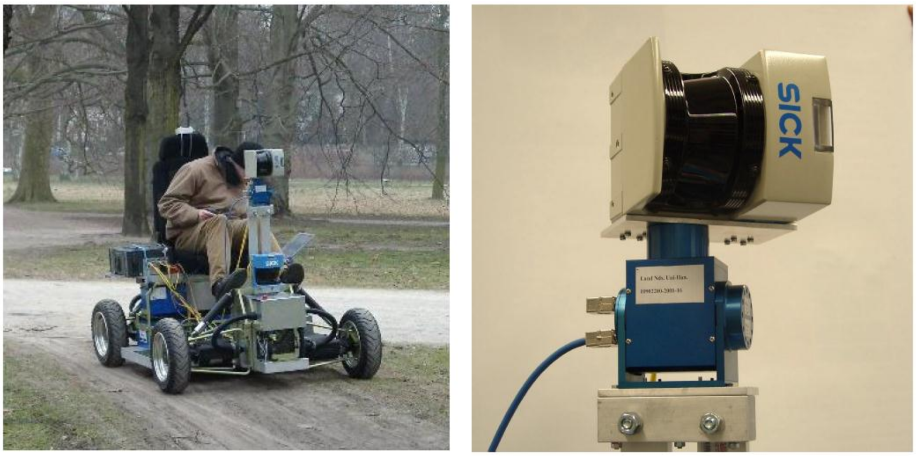

Figure 2.11: 3D Laser Rangefinder [12]

Figure 2.12: 3D Laser Rangefinder [13]

Common solution to add the third dimension to a SICK LMS is provided [11], [12], [13], when the vehicle operates on a terrain and to produce 3D maps of arbitrary, they use a 2D SICK combined with custom-built apparatus. The scanner is mounted in a reciprocating cradle, driven by a constant velocity motor. The main difference between these solutions is the position of the scanner and the rotation axis. But the purpose of all the rangefinders is the same.

Figure 2.13: The HOKUYO Rangefinder [14]

HOKUYO series laser rangefinders are becoming very popular in robotics researches since its features allow to build a 3D laser scanner suitable to be mounted on the base of a medium or small sized robot for navigation, mapping, localization, and robot mobility in indoors scenarios. This sensor has some advantages over the SICK LMS 200 such as: smaller size, lower weight, lower power consumption, and wider field of view and so on. These features have made HOKUYO more suitable for researchs to use instead of Sick sensor for indoor applications in small sized autonomous robota in the latest years.

Figure 2.14: AccuRange Line scanner [15]

This is the sensor of choice for best accuracy in most applications. It uses a visible 670 nm 5-milliwatt laser.

Figure 2.15: AccuRange Mirror Assembly [15]

The AccuRange Line Scanner (Figure 2.15) is precise spinning mirror assembly that coupled with Acuity's laser rangefinder, it creates a laser scanner. The laser scanner sweeps a laser spot through a 360° rotation for the measuring of profiles and scenes.

The AccuRange TM Line Scanner can be used with the AccuRange 4000 to scan and collect distance data over a full circle. The scanner consists of a balanced, rotating mirror and motor with position encoder, and mounting hardware for use with the AccuRange 4000. The scanner deflects the AccuRange beam 90°, sweeping it through a full circle as it rotates. The standard encoder resolution is 4096 counts per revolution. The Acuity laser line scanner has an elliptical mirror situated at a 45° angle to deflect the outgoing laser spot and the return signal.

2.5. Usage of HOKUYO at 3D Scanning

HOKUYO is now, suitable solution for robotics use in 3D point cloud data scenarios. It offers very attractive features in terms of range, accuracy, and working principles. It is a suitable solution to acquire clouds of 3D points in indoor scenarios by modification of scanning axis. This chapter the discussion of possibilities to build a 3D laser scanner on the base of HOKUYO by designing rotating mechanism at one axis is discussed.

The rangefinder examples that are shown in Chapter 2, have illustrated different solutions to acquire 3D points using the sensors and their tilting mechanism. The assumed concept is that since the HOKUYO sensor is 2D laser rangefinder, it is only needed to provide this sensor with the third dimension. The most common way is adding a rotating mechanism in an axis different from that of the rangefinder scanning axis.

Figure 2.16: Rotating Device and Sensor [19]

A DC motor is rotating continuously and measuring the servo position with an encoder, matching the sensor scans and the motor positions by using the synchronous signal provided by HOKUYO sensor [19]. The advantage of this solution is an angular width of 360º, however this solution needs the use of precision encoder and slip rings to allow for a complete rotation. In this design complete rotation is impossible. For a servomotor in open loop configuration, a system control sends the control signal to the servo motor but there is no feedback with the actual position. This solution is low cost and simple. The fact of powering with 5V, and the low power needed by these types of motors, make them highly suitable for robotic solutions.

Figure 2.17: Servomotor, Sensor Mount and Sensor [16]

A servomotor is controlled by one commercial controller without any synchronization with the sensor [16]. This means significant time loss since the data is received by the computer and then the computer gives the order to the servo controller to move the sensor to the next step and then it starts a new scan. It has been used a HITEC servomotor with an angular width of 130º and a resolution of 0.9º.

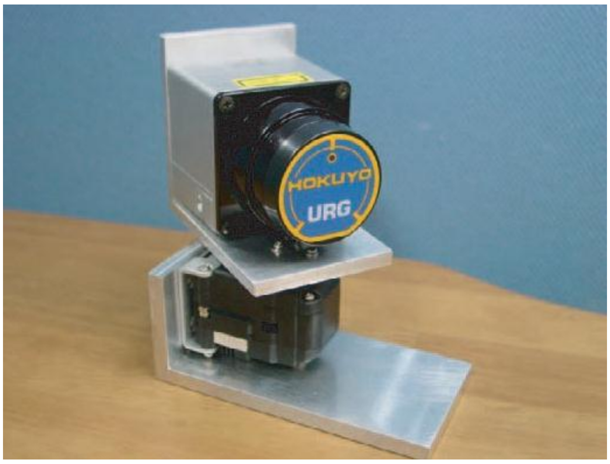

Figure 2.18: Servomotor and Sensor [17]

On the other hand, according to [17], it uses a HITEC servo but with an angular width of 180º, and in ‘full’ scan mode the servo is able to make a full 3D scan with a resolution of 0.5º in 30 seconds. Even they do not provide more details in the paper they mention the use of synchronization between the sensor and the servo controller. Because of its designed construction, it cannot rotate continuously. This designed mechanism reduces its scanning speed and homogeneity of 3D data cloud.

It could be possible to use a servo control with an encoder to feedback the actual position of the servo to the control system. This option would ensure that the servo is in the correct position, but the servo controller would have to be able to send small signals to minimize the error as much as possible, but the servo should be able to react to these small increments the control signal.

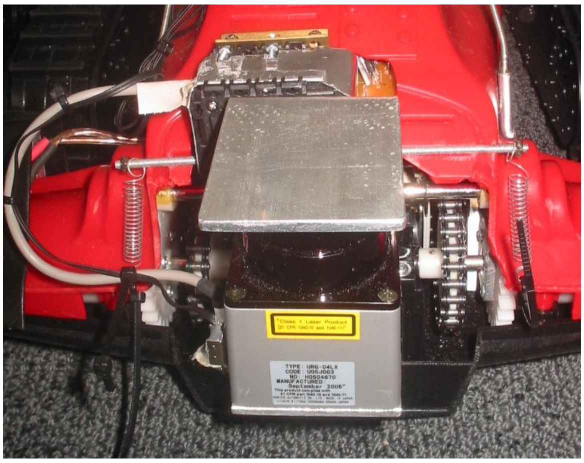

Figure 2.19: Mounted 3D sensor on Redback [18]

According to [18], it uses a servo AX-12; this servo has its own set of commands and has useful features like feedback the actual position, and allows the continuous rotation. However, the control system for this servo it is more complicated that for typical ones.

2.6. Technical Data of HOKUYO URG-04LX

Figure 2.20: HOKUYO URG-04LX [10]

This section concerns with the technical data of the URG-04LX laser rangefinder. It is manufactured by the Japanese company HOKUYO Automatic Co. Ltd. It is shown in Figure 2.20. It processes at very small dimensions (50mmx50mmx70mm) and small weight of only 160 g.

The URG-04LX worked according to principle of the phase shift. A modulated infrared laser beam sent to the surface of the body, whose distance is to be determined. The body reflects the laser beam. For computing the distance of the body, the phase difference of the sent and the reflected laser beam is determined. The measuring range of the URG-04LX lies between 20 mm and 4000 mm, as is shown in its data sheet [10].

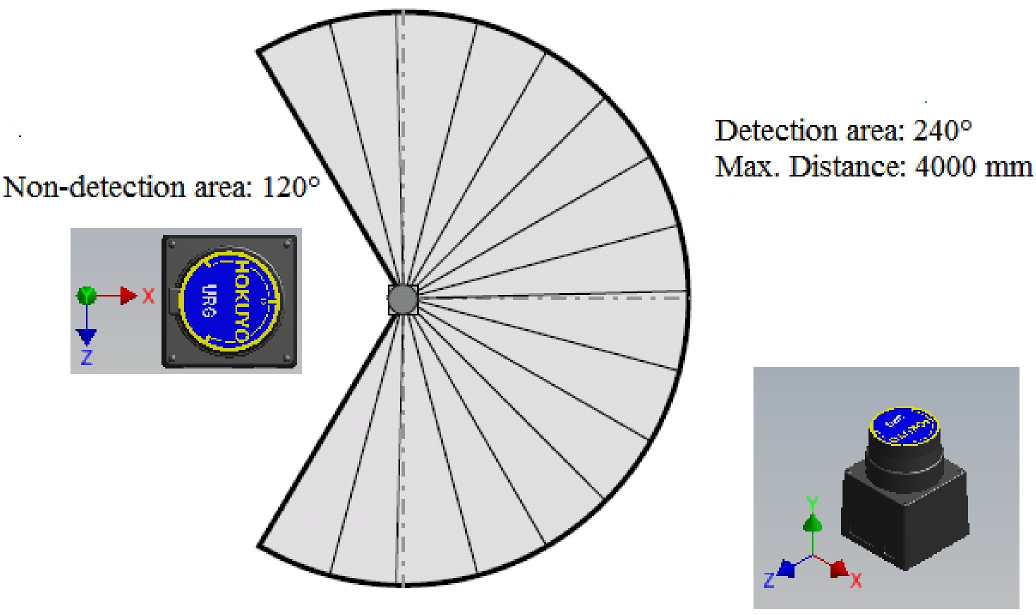

Figure 2.21: HOKUYO's Scanning Angle and Range [10]

The scan area, illustrated in Figure 2.21, is 240° semicircle with maximum radius 4000 mm. Pitch angle is 0.36° and sensor outputs the distance measured at every point (683 steps). Laser beam diameter is less than 20 mm at 2000 mm with maximum divergence 40 mm at 4000 mm.

2.7. Discussion of the Literature Review

Throughout this chapter, a review has been done about the advantages of using laser sensor to retrieve information from the environment without any contact with the target. Different applications require different features, and in terms of laser sensor this would mean that if the application needs very accurate measurements in short range, the best solution is to use triangulation scanners. If the solution requires long range measurements in indoor or outdoor scenarios, the solution is provided by time of flight laser sensor. Acquisition of 3D information is becoming more popular since the advances in computers technology make possible the treatment of large quantity of information. Three dimensional models either single objects or environmental are becoming very common in diverse fields of research. The commercial scene offers several 3D laser scanners very accurate and able to work in very large range (up to many meters). However, they are very expensive and heavy, and its use is limited to big projects, they are not suitable for using in robotics. Now it is not easy to find a commercial 3D laser sensor suitable for robotics use, with relative low cost, and the required features for this application. This is why lately, robotic research groups around the world, in order to provide 3D perception to their robots, they have opted for building their own three dimensional laser scanner. With this purpose, most groups have used 2D laser rangefinder, the most popular sensor used with this purpose has been SICK LMS 200, since it offers: relative low weight (4.5 kg), relative low size, the ability of working in outdoor/indoors scenarios, a field of view of 120º, and an accuracy of 10mm. In spite of the fact that SICK LMS 200 has been widely used in the robotics field, recently the HOKUYO sensor is becoming very popular in robotics laboratories.

HOKUYO sensor is significantly smaller and lighter than SICK sensor. Moreover, it offers a wider field of view (240º). HOKUYO sensor has as a disadvantage that it is more suitable for indoor scenarios and its range is only 4 meters while SICK range is 80 meters. HOKUYO manufacturer has also long range rangefinder models which are suitable for outdoor usage. For outdoor applications, usage of SICK is more common than HOKUYO. For indoor usage, HOKUYO sensor is becoming more popular in the robotics field. This sensor makes possible the implementation of a 3D laser scanner using a servo digital motor, since it has a low weight and low power consumption.

In this project, it has been looked for a solution to acquire 3D laser points, to be mounted on the base of a robotic platform, to work in indoor scenarios.

After the discussion, it is concluded that the best solution at the moment is to build a 3D laser rangefinder on the base of a 2D HOKUYO sensor.

In this chapter, literature has been conducted for commercial 3D laser rangefinders and their usage at 3D scanning. HOKUYO laser rangefinder has been seen for possible solution at the moment but final solution has been given after comparison of other possible methods by the help of decision matrix in Chapter 3.

CHAPTER 3

SYSTEM DESIGN

3.1. Design Process

The design process can be decomposed into three general phases: conceptual design, embodiment design and detail design. The conceptual design and embodiment design have some sub stages.

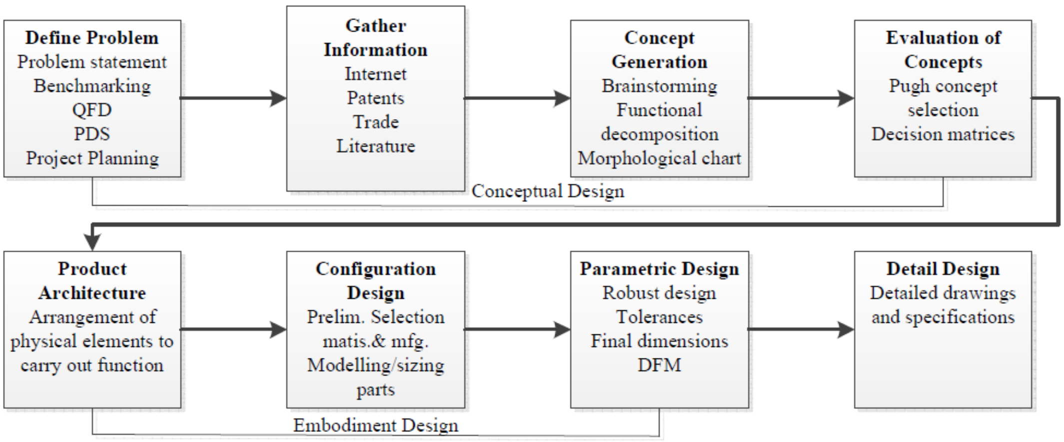

Figure 3.1: Steps in Engineering Design [39]

The conceptual design stage can further be decomposed into four steps:

- Define problem,
- Gather Information,
- Concept generation,
- Evaluation of concepts.

Embodiment design can be decomposed into three steps:

- Product architecture
- Configuration design
- Parametric design

And detail design finalizes the design progress. Graphical illustration of engineering design steps has been given in Figure 3.1.

3.2. Define Problem

In this phase problem statement is clarified. The problem chosen for this study is "Designing of a Scanning Platform for Collecting 3D Depth Data".

Benchmarking is a method to measure a design against the best designed product in the area of selected field. The information under this topic has been mainly taken from the HOKUYO URG-04LX which is mentioned in section 2.6 Technical Data of HOKUYO URG-04LX. Sub steps of benchmarking have been given below:

- Scanning speed: 100 msec. at 2D,
- Scanning angle: 240º at 2D,
- Scanning range: From 20 to 4095 mm,
- Weight: 160 gr,
- Scanning environment: Indoor,
- Ability to 3D scanning: Not available.

Designed product requirements should be translated into performance, time, cost and quality metrics. They can be summarized as:

- Performance: What design should do when it is in operation?
- Time: All time aspects of the design.

- Cost: All monetary aspects of the design.
- Quality: Totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs.

These aspects can be seen in QFD – Quality Function Development which is given below:

- Fast,
- Reliable,
- Light weight,
- Accurate,
- Adjustable,
- Programmable,
- Splash proof,
- Low cost.

In PDS – Product Design Specification, the purpose is measuring the quality of design. To see "how much is good", setting engineering targets (performance targets) have to be done. PDS contains all the facts related to the outcome of the product development. Related Product Design Specification has been given below:

- Scanning resolution less than 0.36º,
- Scanning speed: Between 0 and 500 rpm,
- Scanning time: Adjustable,
- Scanning range: Minimum 4 meters,
- Weight: Less than 5000 grams,
- Scanning Angle: 360º,
- Power consumption: Minimum,
- Splash proof: Required,
- Vibration level: Minimum (Balanced design).

First step of conceptual design phase has been completed. All sub-steps of this step has been illustrated in Figure 3.24.

An ATV with maximum 20 km/h travelling speed has been taken as reference robotic vehicle for outdoor usage. According to American National Standard for four wheel all terrain vehicles ANSI / SVIA – 1 – 200X maximum braking distance has to be S value which has been given below with a formula:

$$S \leq V / 5.28 \tag{3.1}$$

where S is the brake stopping distance (m) and V is the braking test speed (km/h).

Maximum stopping distance has been calculated as 3.78 meters for 20 km/h speed. With today’s ongoing braking technologies, commercial ATVs braking capability is about three times better than maximum braking distance which is calculated. 4 meters depth distance capability has been seen enough to take a necessary response for braking. HOKUYO URG-04LX laser rangefinder, which is mentioned in section 2.6 Technical Data of HOKUYO URG-04LX, has been taken as a device for conceptual design phase. Depending on HOKUYO URG-04LX’s technical data; scanning resolution, scanning speed, power conception levels have been conducted in section 2.6 Technical Data of HOKUYO URG-04LX. Capability of scanning angle has been decided with this thesis objective as a full scan. Full scanning requires the balanced rotation. Considering the carrying capacity of the ATV and the weight of the SICK LMS series which are commonly used in indoor robotic applications, the maximum weight has been chosen as 5000 gr.

3.3. Gather Information

In this phase needed information for design process is searched over internet, patents, trade and literature. All these headlines have to be gathered before concept generation phase which is the third step of Conceptual Design. For selected problem statement internet investigation has been done in Chapter 2. As mentioned in section 2.2 3D Depth Measurement Using Time Flight Method phase shift and time of flight methods are commonly used for range acquisition. Gathered information from internet has been given below:

- Range Acquisition,
    - Optical,
        - Phase shift method,
        - Time of flight method.

An important step for this phase is the patent search. For range acquisition by using a rangefinder, there are several patents in literature. Patents which are seen helpful for this thesis are selected and investigated under the patents sub-sections. Related patents with detailed summary have been given below:

Patent US 7,430,068 B2 claims that “A laser scanner has a first axis and a second axis extending essentially transversely to the first axis. A measuring head is adapted to be rotated about the first axis. The measuring head has at least a first, a second, and a third module, wherein at least the first module and the third module are releasably connected to each other. A first rotary drive for rotating said measuring head is comprised within the first and the second modules. A rotary mirror is adapted to be rotated about the second axis. The rotary mirror is comprised within the third module. A second rotary drive is provided for rotating the rotary mirror. The second drive is likewise comprised within the third module. A transmitter is provided in the measuring head for transmitting a light beam. A receiver is provided in the measuring head for receiving the light beam after a reflection thereof by an object located at a distance from the laser scanner. A computer is provided in the measuring head for processing signals embedded within the received light beam.” [27].

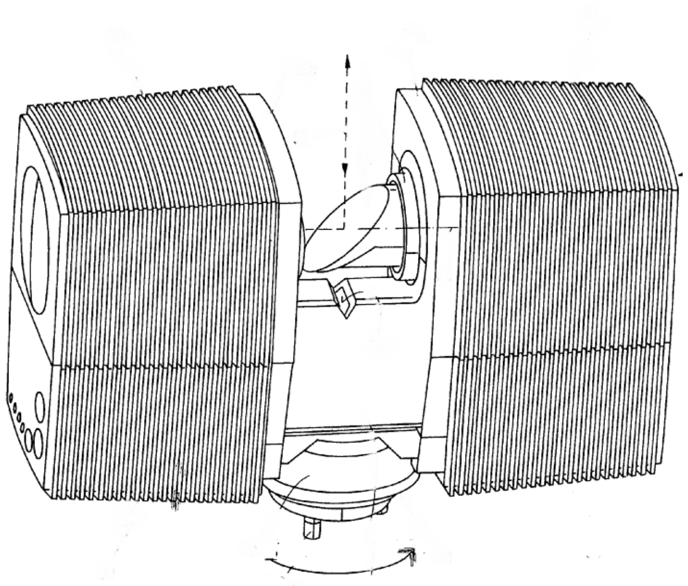

Figure 3.2: Patent US 7,430,068 B2 [27]

Patent US 2008/0246943 A1 claims that “A 3D pulsed laser projection system scans an object to produce a dense 3D point cloud and projects a laser light beam onto an object as a glowing template. A high-sensitivity optical feedback system receives and detects a feedback beam of the output beam light diffusely reflected from the object. The feedback light and projected beam shares the same beam path between steering mirrors and the object. A light suppression component controls stray scattered light, including ambient light, from being detected. A time-of-flight measurement sub-system provides a distance to object measurement for projected pulses. An acousto-optical modulator, variable gain detected signal amplification and variable photo-detector power together produce a dynamic range for detected reflected feedback signals of at least 100,000, and up to 500, 000. Optical fiber cables spatially filter scattered light and isolate the photo-detectors thermally. The laser is preferably pulsed at least 50 kHz, with sampling of the projected and feedback reflected optical pulse signals at a sampling rate of up to 10 giga samples per second.” [28].

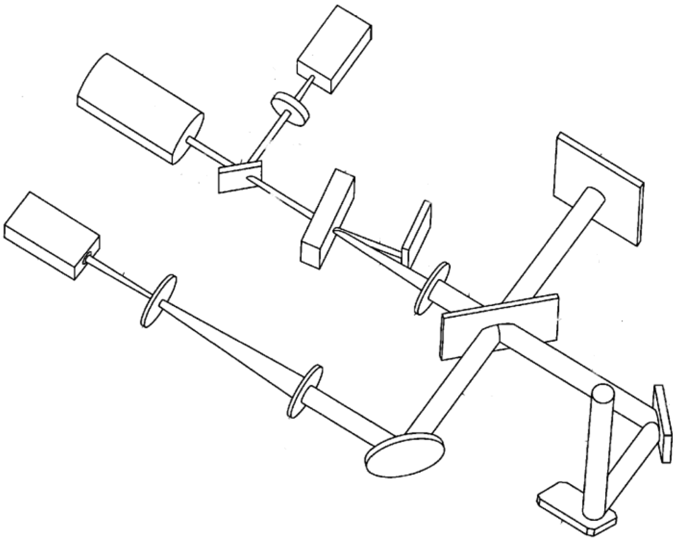

Figure 3.3: Patent US 2008/0246943 A1 [28]

Patent US 7,403,269 B2 claims that “Scanning rangefinder of simple, compact construction. The rangefinder is furnished with: an outer cover in which a transparent window is formed; a cylindrical rotary unit inside the outer cover; a scanning/receiving window provided in the rotary unit; a dual scanning/receiving mirror disposed, angled, along the rotational axis of the cylindrical rotary unit; a motor for rotationally driving the rotary unit; a disk part arranged in the cylindrical rotary unit, anchored in an inside region thereof; a beam projector anchored in a location where it is disposed slightly spaced apart from the rotational axis of the rotary unit; and a light receiver anchored to, arranged coincident with the rotational axis of, the disk part in the inside region of the rotary unit, and connected to a distance computation circuit.” [29].

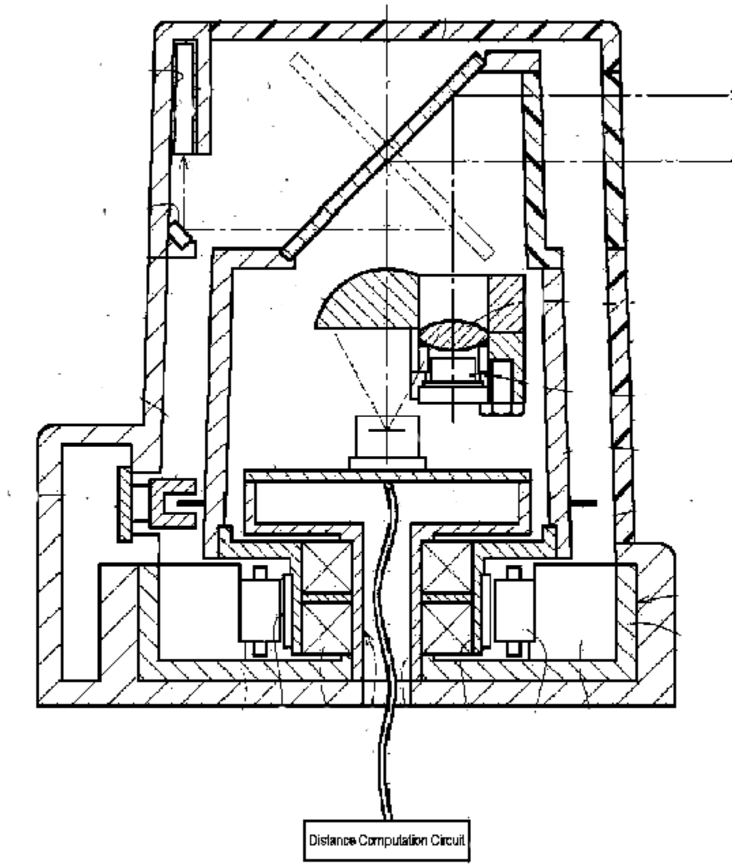

Figure 3.4: Patent US 7,403,269 B2 [29]

Patent US 7,933,055 B2 claims that "A laser scanner for detecting spatial surroundings comprises a stator, a rotor, mounted on the stator to be rotatable about a first rotational axis, and a rotary body, mounted on the rotor to be rotatable about a second rotational axis. A laser source and a detector are arranged in the rotor. One optical link each is configured on the second rotational axis on every side of the rotary body between the rotor and the rotary body so that emission light can be introduced by the laser source into the rotary body via the first optical link and reception light can be discharge from the rotary body via the second optical link. A first rotary drive drives the rotor and a second rotary drive drives the rotary body. Two goniometers and evaluation electronics which are connected to the laser source and the detector allow association of a detected distance with a corresponding direction. The rotary body can have a very compact design, is completely passive and therefore does not require any power supply or transmission of signals." [30].

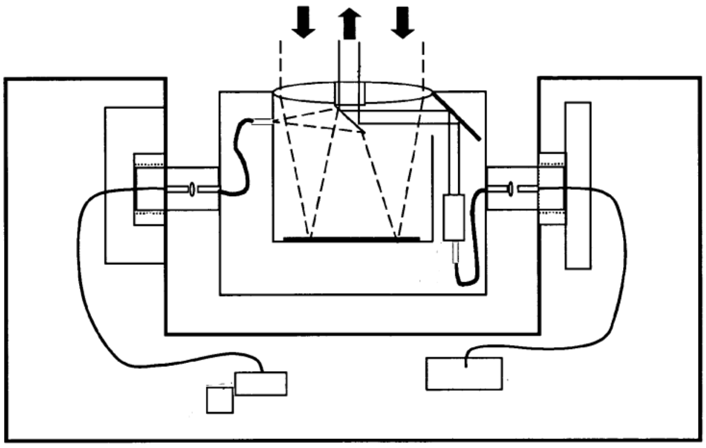

Figure 3.5: Patent US 7,933,055 B2 [30]

The manufacturers offer a wide product range of laser rangefinder that can be applied in different fields; from measurements in buildings or tunnels measurements to very accurate measurements of defects in small objects. Some of them offer solutions to acquire 3D point clouds alongside with the software required for the treatment of raw (optical) data. For selected problem statement, some rangefinders and their ability of scanning, stated in market, have been given below:

- Sick (2D),
- HOKUYO (2D),
- Acuity (2D),
- Ibeo (2D and 3D),
- Riegl (2D and 3D).

Literature investigation has been done partly in Chapter 2, 2.3 Rangefinder Sensors and Comparison and 2.4 Reconstruction of a 2D Rangefinder for 3D Scanning, as mentioned in these sections rotating a 2D laser rangefinder is a common way of getting 3D data point cloud. The idea is simple; the scanning system is provided by rotating laser rangefinder at z-axis in one dimension. Laser rangefinder will also measures the distance as the second dimension of the system. Also it rotates the laser beam at another axis which is different from the measuring distance axis and rotary z-axis. In this way, the scanning system has the three-dimensional scanning ability. The other two methods which are mentioned in Literature review sub folders in, depends on the idea of tilting a laser beam with a mirror by rotating or tilting it. These methods in literature are:

- Scan by rotating of a 2D laser rangefinder,
- Scan by rotating of two mirrors with a reflected laser beam,
- Scan by tilting a mirror at two axis with a reflected laser beam.

Single & dual axis scanning galvanometer system is being used for tilting a laser beam at two different axis (x-axis and y-axis) [31].

Figure 3.6: Thorlabs Dual Axis Scanning Galvanometer [31]

Three-axis electromagnetically actuated micromirror is a good example of tilting a mirror at two axis. It uses a external magnetic field for tilting itself. But it’s low field of view is disadvantage of this design [32].

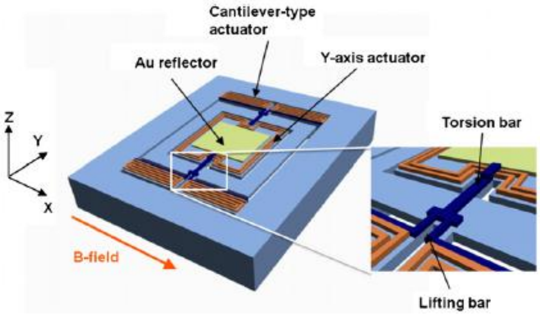

Figure 3.7: Electromagnetically Actuated Micromirror [32]

Second step of conceptual design phase has been completed. All sub steps of this phase has been illustrated in Figure 3.24.

3.4. Concept Generation

In this phase design problem asks to come up with a solution that performs an overall function (Figure 3.24). Brainstorming, functional decomposition and morphological chart are main sub-titles of concept generation phase. Brainstorming is a technique that, during a group session one proposed idea may trigger the other ideas and the process continues. Combinations, substitutions, modifications, reverse or other use of generalized categories can help at brainstorming stage. There are different ways of getting 3D data point cloud. The methods are given below:

- Laser rangefinder measures the distance as the first dimension of the system. A mirror tilts the laser beam at x-axis and y-axis which is different from the measuring distance axis. The scanning system will have the three-dimensional scanning ability. Given methods can be used for tilting the mirror:
    - MEMS – Micro Electro Mechanical Systems,
    - Permalloy,
    - Terfenol-D,
    - Spherical Motor,
    - Piezoelectric Actuator,
    - Galvo Scanning Heads,
    - Steward Platform.
- The scanning system is provided by rotating laser rangefinder or another mirror at z-axis in one dimension. Laser rangefinder measures the distance as the second dimension of the system. Also it rotates the laser beam at another axis which is different from the measuring distance axis and rotary z-axis. In this way, the scanning system has the three-dimensional scanning ability.

This design allows the scanning platform, continuous scanning capability at three dimensional.

  - Using a 2D laser rangefinder and a rotating mirror,
  - Rotating a laser rangefinder with a capability of 2D distance measurement.

- The required data is provided by rotating laser rangefinder at two different axis. Laser rangefinder measures the distance as the third dimension of the system. This design allows the scanning platform, continuous scanning capability at three dimensional.
- Multiple rangefinders can be used for getting 3D point cloud data.

Functional decomposition is used to understand the processes and can be used to help solve problems. For this thesis, the required solution is to get a 3D point cloud data of a selected environment. Functionality of some common devices has been given in Table 3.1 for functional decomposition purpose.

Table 3.1: Functionality of Some Common Devices

Device	**Input**	**Function**	**Other effects**	**Output**
Rangefinder	Electrical energy	Measure distance	1D or 2D Measuring	Distance data
Motor	Electrical energy	Convert electrical energy to mechanical energy	Thermal energy generated	Rotating mechanical energy
Rotary encoder	Mechanical rotation	Provide information about the motion of the shaft	-	Analog or digital data
Gear	Rotating mechanical energy	Change speed of rotation	Change torque of rotation	Rotating Mechanical energy
Slipring	Electrical energy	Transfer electrical energy at rotary parts	Damping vibration	Electrical energy
Bearing	Rotation	Reduce friction	Connect rotary parts	Rotation with reduced friction

3.4.1. Morphological Chart

A morphological chart is an ideation tool that represents a large qualitative design space. Currently, morphological charts use a function list as the function representation of the design problem. Combining one means from each function produces an integrated conceptual design solution. By repeating this process with all possible combination that contained in the morphological chart, a long list of conceptual design solutions is generated, although not all are practical.

Table 3.2: Morphological Chart

Functions	**Solutions**			
Distance Measuring	Ambient Light (D1)	Structured Light (D2)	Ultrasound (D3)	Laser Light (D4)
Scanning	Rotating (S1)	Tilting (S2)	Reflecting (S3)	-
Motion	Electrical Motor (M1)	Magnetic Force (M2)	Hydrolic Power (M3)	-
Data Transferring	Slipring (C1)	Wireless (C2)	Cable (C3)	-
Bearing	Mechanical (B1)	Air (B2)	Liquid (B3)	-

Functions and related solutions have been listed in Table 3.2. Depending on the table, conceptual design solutions have been generated and listed below:

- D4, S1, M1, C1/C2, B1, Rotate Laser Rangefinder and/or Mirror – Combinations,
- D1/D2/D4, S2, M2, C1/C2/C3, B1/B3, MEMS,
- D4,S1/S2/S3, M2, C2/C3, B1, Permalloy with Magnetic Forces, Terfenol-D with Displacement Multiplier,
- D4, S1, M2, C1/C2, B1, Piezoelectric Actuator,

- D1/D2/D4, S1/S2/S3, M2, C1/C2/C3, B1, Spherical Motor,
- D4, S1/S3, M1, C1/C2/C3, B1, Galvo Scanning Heads / Rotate with a Mirror,
- D1/D2/D4, S2/S3, M1/M3, C2/C3, B1, Steward Platform.

Generated conceptual design solutions are conducted and best solution is decided with a decision matrix which is given in Table 3.3.

3.4.2. Literature Review After Brainstorming Session

MEMS (Micro Electro Mechanical Systems) mirror technology is commonly used for miniature laser scanning. MEMS based laser scanning module which is used in industrial, medical and consumer products requiring ultra fast and accurate laser scanning. But their low field of view which is caused by non-sufficient tilting angle limits their usage. According to [33], "MEMS scanning micro-mirrors were developed using various actuation techniques, including thermal, electrostatic, piezoelectric and magnetic. The initial technology choice strongly depends on the applications and the required performances in terms of scanning speed, scanning angle, shock resistance, power consumption and packaging compatibility. Magnetic actuated MEMS micro-mirrors have been developed for the laser scanning projection purpose."

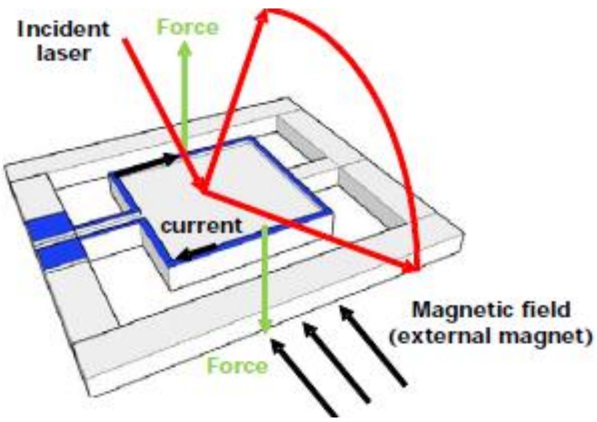

Figure 3.8: MEMS Mirror Magnetic Actuation Principle [33]

Permalloy, a Nickel-Iron-Molybdenum alloy, provides very high initial and maximum magnetic permeabilities and minimal core losses at low field strengths. This vacuum-melted product also offers the advantages of small size and weight in magnetic core. Common usage of permalloy has been illustrated in Figure 3.9. Its low field of view and control difficulties limit their usage. According to [34], “Magnetic behavior of polymer-based scanners is studied in detail with emphasis on a new magnetic actuator model and deflection experiments. A 30-μm-thick permalloy sheet is plated on a polymer cantilever scanner and actuated using an external coil. Shape anisotropy of the thin, soft magnetic film is explored for push and pull operation in different configurations. Two-dimensional (2D) scanning utilizing the orthogonal modes of the scanner, using only one actuation coil is presented. The system consists of a narrow cantilever beam supporting a rectangular mirror and an electromagnet for actuation. Cross section between AA’ line is shown indicating the materials used in the structure. Torsional rotation and out-of-plane bending mode motion directions are marked with arrows.”

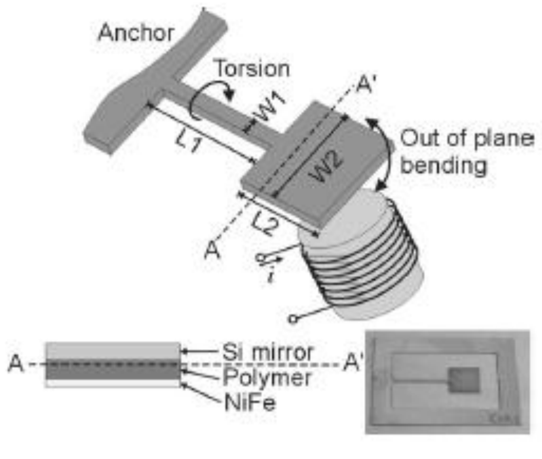

Figure 3.9: Electrocoil Actuated Scanner [34]

According to [34], “Magnetostriction is the property that causes certain ferromagnetic materials to change shape in a magnetic field also called the Joule Effect. Terfenol-D is said to produce "giant" magnetostriction, with strains 100 times greater than classical magnetostrictive materials such as iron. Magnetic domains in the crystal rotate when a magnetic field is applied, providing proportional, positive and repeatable expansion in microseconds."

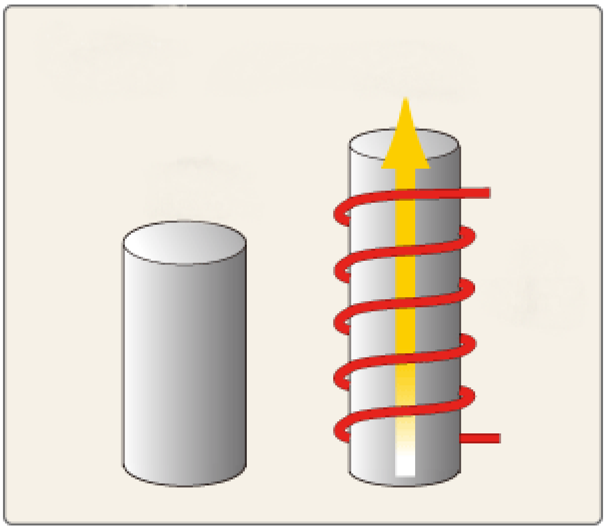

Figure 3.10: Magnetostriction Principle [34]

Magnetostrictive actuator, Terfenol-D, has lots of advantage over voice coil and piezoelectric type actuators. It has greater strain and faster response. Its elongation under magnetic forces is not enough even with a "displacement amplification [35]". According to [36], "Magnetostrictive material, as a special smart material, can expand or shrink quickly and forcefully when placed in a magnetic field. Two magnetostrictive actuators are mounted along two orthogonal directions for two dimension rotation. TbxDy(1-x)Fe2 has the advantages of big displacement, high resolving power and big output force, it has been considered as the most ideal and valuable magnetostrictive material. Giant magnetostrictive actuators are tending to replace piezoelectric actuators in many applications owing to their giant magnetostrain and fast response. "

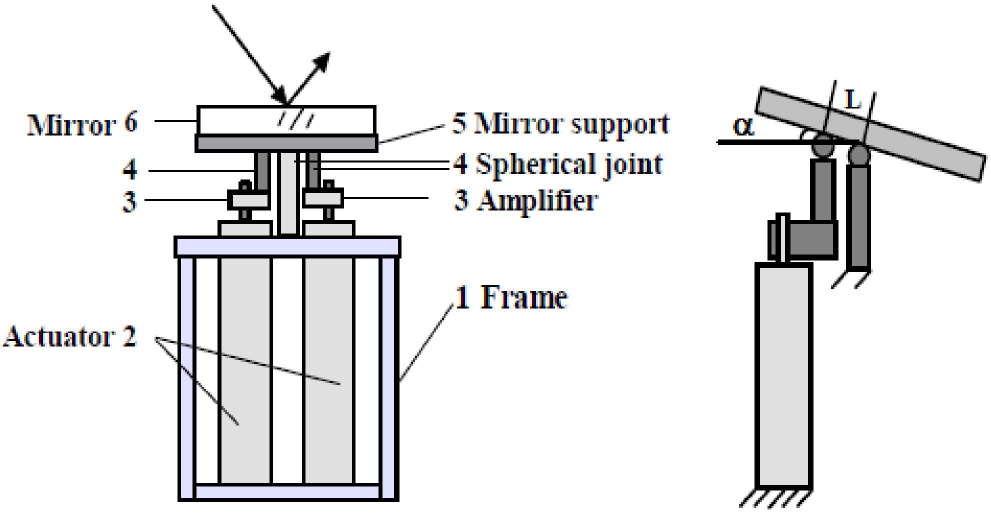

Figure 3.11: Schematic of Fast Magnetostrictive [36]

The spherical geometry of the proposed motor makes it different from conventional motors especially regarding the structural design. Commonly, motors are design with a cylindrical geometry. Both the rotor poles and the stator poles are positioned around the rotor and stator structures. However this geometry only allows the motor to rotate, in both directions, in one axis. A spherical motor has a capability of tilting and turning at three degrees of freedom. This capability of spherical motor gives a chance to think about using it in a mirror tilted application. But its big sizes, control difficulties and slow responses make it difficult. According to [37], "This drive can be used for machine tools and robots to replace conventional rotating or linear machines which are connected in series or parallel. The proposed motor consists of a rotor sphere with permanent magnets and an outer stator core casing with 96 stator poles and windings. The currents of the stator coils have to be controlled individually because the pole pitch can vary continuously during operation."

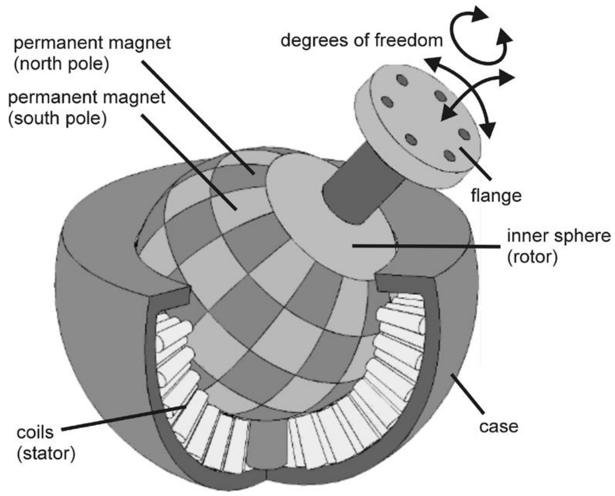

Figure 3.12: Spherical Motor [37]

According to [38], “The movement of parallel manipulator is carried out by controlling the length of links in usual condition. In order that the Stewart platform can move at will when the length of links changes in a determinate region, we discuss the problems about the manipulator configuration and link length. Sixteen kinds of extreme configurations for Stewart platform are described with the vector expressions of link lengths. The safety length of links is solved, which makes the manipulator work safely in the safety length area of links. The relationship between the safety length of links and the structural parameters is analyzed by numerical examples.” It is hard to use a Steward Platform because of size, low field of view and working speed.

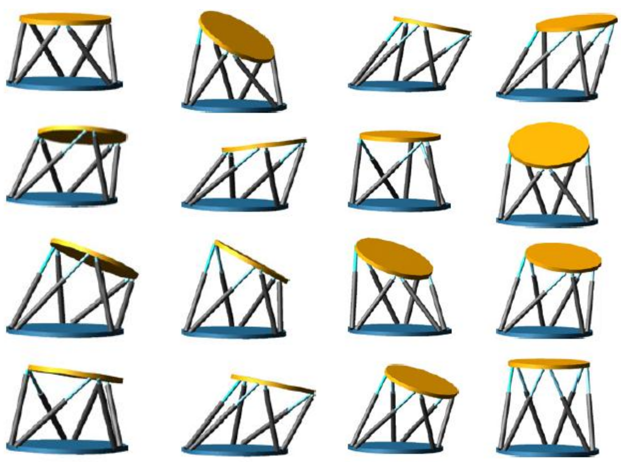
Figure 3.13: Steward Platform [38]

3.5. Evaluation of Concepts

The last step of Conceptual Design is Evaluation of Concepts phase. Evaluation based on judgement of feasibility of the design. The technology used in the design must be mature enough that does not need any additional research. Generated concepts should be manufactured with available processes and critical parameters and they should be under the control of identified functions which are defined in functional decomposition part. To make a valid comparison, concepts must have the same level of abstraction. As shown in Figure 3.1, for Pugh concept, selection method of some important points have to be examined. Choosing the criteria by which the concepts is evaluated, formulating the decision matrix, clarifying the design concepts and evaluating the ratings have to be done to make a correct selection. All these points have been conducted when the decision matrices are constructed.

3.5.1. Decision Matrices

The weighted criteria matrix is a valuable decision making tool that is used to evaluate alternatives based on specific evaluation criteria weighted by importance. Weighting factors are used to define the level of importance of criteria. Assigning meaning to weighting factors is subjective. For this reason, it is important to keep the number of weighting factors small. For this reason, scale 1 to 10 has been selected. The increased number shows the criteria capability from poorer to better.

As an extension of morphological chart which is mentioned in section 3.4.1 Morphological Chart, Method Selection of Designing a Scanning Platform for 3D Depth Data weighted decision matrix has been done and given in Table 3.3. Selected parameters for criteria are Fast, Reliable, Light Weight, Accurate, Programmable, Splash-Proof, Scanning Angle, Minimum Power Consumption and Vibration Level.

The winner of decision matrix for method selection is Rotate Laser Rangefinder and/or Mirror – Combination with a score of 7,8. This score clarifies the method selection as Rotate Laser Rangefinder and/or Mirror – Combination. The decision matrix is rerun to make a decision for finding the best solutions of design problems which are mentioned below;

- Laser rangefinder selection,
- Method of tilting laser beam,
- Motor selection,
- Power transfer,
- Data transfer.

A category score is calculated by summing the weighted scores for each criterion in the category and dividing by the sum of the weights for the criteria in the category. A weighted category score is calculated by multiplying the category score by the category weight. The final score is calculated by summing the weighted category scores and dividing by the sum of the category weights. Each category has a weight value to examine the categories for which one is more important for design selection.

In Table 3.3, Table 3.4, Table 3.5, Table 3.6, Table 3.7 and Table 3.8 higher scores indicate winner of the decision matrix and the highest scores after the winner indicate the best applicable solution in case the winner solution can’t be applied.

Table 3.3: Method Selection of Designing a Scanning Platform for 3D Depth Data

Method Selection of Designing a Scanning Platform for 3D Depth Data		Rotate Laser Rangefinder and/or Mirror - Combinations		MEMS		Permalloy with Magnetic Forces		Terfenol-D with Displacement Multiplier		Spherical Motor		Piezoelectric Actuator		Galvo Scanning Heads / Rotate with a Mirror		Steward Platform	
Category	**Weight**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
Fast	9.0	7.0	63.0	5.0	45.0	3.0	27.0	4.0	36.0	2.0	18.0	1.0	9.0	9.0	81.0	2.0	18.0
Reliable	7.0	7.0	49.0	4.0	28.0	2.0	14.0	5.0	35.0	4.0	28.0	3.0	21.0	8.0	56.0	10.0	70.0
Light Weight	6.0	6.0	36.0	10.0	60.0	7.0	42.0	4.0	24.0	2.0	12.0	5.0	30.0	7.0	42.0	2.0	12.0
Accurate	8.0	8.0	64.0	4.0	32.0	3.0	24.0	5.0	40.0	6.0	48.0	5.0	40.0	7.0	56.0	9.0	72.0
Programmable	8.0	9.0	72.0	4.0	32.0	4.0	32.0	4.0	32.0	8.0	64.0	4.0	32.0	10.0	80.0	10.0	80.0
Splash-Proof	4.0	9.0	36.0	3.0	12.0	3.0	12.0	3.0	12.0	1.0	4.0	2.0	8.0	9.0	36.0	3.0	12.0
Scanning Angle	10.0	10.0	100.0	3.0	30.0	5.0	50.0	1.0	10.0	7.0	70.0	6.0	60.0	3.0	30.0	6.0	60.0
Power	3.0	5.0	15.0	10.0	30.0	6.0	18.0	6.0	18.0	3.0	9.0	10.0	30.0	7.0	21.0	5.0	15.0
Vibration	5.0	6.0	30.0	3.0	15.0	1.0	5.0	10.0	50.0	0.1	0.3	10.0	50.0	9.0	45.0	7.0	35.0
Total	60.0	67.0	465.0	46.0	284.0	34.0	224.0	42.0	257.0	33.1	253.3	46.0	280.0	69.0	447.0	54.0	374.0
Score			7.8		4.7		3.7		4.3		4.2		4.7		7.5		6.2

Table 3.4: Rangefinder Selection

			Acuity (1D)		Acuity (2D)		Hokuyo		Ibeo		Sick		Riegl	
Weght: 6.0	Criteria	Weight	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Rangefinder Selection	Light Weight	7.0	5.0	35.0	3.0	21.0	10.0	70.0	4.0	28.0	4.0	28.0	3.0	21.0
	Cost	5.0	6.0	30.0	5.0	25.0	9.0	45.0	3.0	15.0	5.0	25.0	4.0	20.0
	Accuracy	7.0	9.0	63.0	9.0	63.0	5.0	35.0	9.0	63.0	8.0	56.0	6.0	42.0
	Splash-Proof	3.0	8.0	24.0	7.0	21.0	6.0	18.0	9.0	27.0	8.0	24.0	7.0	21.0
	Scanning Range	4.0	5.0	20.0	5.0	20.0	2.0	8.0	9.0	36.0	7.0	28.0	10.0	40.0
	Scanning Angle	3.0	3.0	9.0	7.0	21.0	9.0	27.0	8.0	24.0	6.0	18.0	10.0	30.0
	Power	3.0	10.0	30.0	6.0	18.0	9.0	27.0	7.0	21.0	6.0	18.0	1.0	3.0
	Total	32.0	46.0	211.0	42.0	189.0	50.0	230.0	49.0	214.0	44.0	197.0	41.0	177.0
	Score			6.6		5.9		7.2		6.7		6.2		5.5
	Weighted			39.6		35.4		43.1		40.1		36.9		33.2

Table 3.5: Method of Tilting Laser Beam

			Rotate LRF and a mirror at one-axis (separately)		Rotate two mirrors at different-axis		Rotate LRF at two-axis		Rotate LRF at one-axis	
Weight: 8.0	**Criteria**	**Weight**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
Method of Tilting Laser Beam	**Scanning Speed**	9.0	5.0	45.0	9.0	81.0	3.0	27.0	7.0	63.0
	Light Weight	6.0	5.0	30.0	10.0	60.0	3.0	18.0	6.0	36.0
	Moment of Inertia	4.0	4.0	16.0	10.0	40.0	3.0	12.0	5.0	20.0
	Ease of maintenance	2.0	5.0	10.0	6.0	12.0	7.0	14.0	9.0	18.0
	Field of View	5.0	6.0	30.0	2.0	10.0	9.0	45.0	8.0	40.0
	Scanning Angle	10.0	6.0	60.0	2.0	20.0	9.0	90.0	8.0	80.0
	Vibration Level	4.0	6.0	24.0	9.0	36.0	5.0	20.0	7.0	28.0
	Total	40.0	37.0	215.0	48.0	259.0	39.0	226.0	50.0	285.0
	Score			5.4		6.5		5.7		7.1
	Weighted			43.0		51.8		45.2		57.0

Table 3.6: Motor Selection

Weight: 4.0	Criteria	Weight	Universal Motor		Switched Reluctance Motor		Pancake DC		Brushed DC with Encoder and Gear		Brushless DC with Encoder and Gear		Stepper DC	
			Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Motor Selection	**Cost**	4.0	7.0	28.0	7.0	28.0	5.0	20.0	3.0	12.0	3.0	12.0	3.0	12.0
	Availability	10.0	1.0	10.0	1.0	10.0	1.0	10.0	10.0	100.0	10.0	100.0	1.0	10.0
	Light Weight	6.0	6.0	36.0	6.0	36.0	5.0	30.0	6.0	36.0	6.0	36.0	7.0	42.0
	Long Life	3.0	3.0	9.0	7.0	21.0	5.0	15.0	5.0	15.0	6.0	18.0	7.0	21.0
	Torque	3.0	8.0	24.0	5.0	15.0	6.0	18.0	9.0	27.0	9.0	27.0	7.0	21.0
	Speed	9.0	8.0	72.0	6.0	54.0	3.0	27.0	5.0	45.0	5.0	45.0	8.0	72.0
	Precision	10.0	2.0	20.0	3.0	30.0	3.0	30.0	8.0	80.0	7.0	70.0	10.0	100.0
	Control	10.0	3.0	30.0	3.0	30.0	4.0	40.0	8.0	80.0	7.0	70.0	9.0	90.0
	Total	55.0	38.0	229.0	38.0	224.0	32.0	190.0	54.0	395.0	53.0	378.0	52.0	368.0
	Score			4.2		4.1		3.5		7.2		6.9		6.7
	Weighted			16.7		16.3		13.8		28.7		27.5		26.8

Table 3.7: Power Transfer

Weight: 3.0			Slipring with Stator Block		Taco Generator		Slipring with Optic		Microwave /Electromagnetic Radiation		Electro Magnetic Induction	
	Criteria	**Weight**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
Power Transfer	**Cost**	3.0	7.0	21.0	10.0	30.0	4.0	12.0	1.0	3.0	1.0	3.0
	Easy Maintenance	6.0	7.0	42.0	6.0	36.0	7.0	42.0	1.0	6.0	1.0	6.0
	Long Life	9.0	6.0	54.0	4.0	36.0	8.0	72.0	9.0	81.0	9.0	81.0
	Rotation Ability	10.0	8.0	80.0	5.0	50.0	8.0	80.0	7.0	70.0	7.0	70.0
	Noise Production	10.0	7.0	70.0	5.0	50.0	5.0	50.0	3.0	30.0	3.0	30.0
	Apparatus Needed	4.0	9.0	36.0	4.0	16.0	9.0	36.0	10.0	40.0	10.0	40.0
	Moment of Inertia	9.0	9.0	81.0	4.0	36.0	9.0	81.0	1.0	9.0	1.0	9.0
	Total	51.0	53.0	384.0	38.0	254.0	50.0	373.0	32.0	239.0	32.0	239.0
	Score			7.5		5.0		7.3		4.7		4.7
	Weighted			22.6		14.9		21.9		14.1		14.1

Table 3.8: Data Transfer

			Infrared		GSM (2G. 3G)		DSRC		WiMAX		RFID Radio Frequency Indetification		Satellite		Slipring		Bluetooth		IEEE 802.11	
Weight: 6.0	**Criteria**	**Weight**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
Data Transfer	**Cost**	3.0	10.0	30.0	1.0	3.0	7.0	21.0	5.0	15.0	5.0	15.0	2.0	6.0	6.0	18.0	9.0	27.0	8.0	24.0
	Easy Maintenance	6.0	9.0	54.0	9.0	54.0	6.0	36.0	5.0	30.0	6.0	36.0	3.0	18.0	7.0	42.0	8.0	48.0	10.0	60.0
	Long Life	9.0	9.0	81.0	6.0	54.0	8.0	72.0	8.0	72.0	7.0	63.0	5.0	45.0	6.0	54.0	9.0	81.0	9.0	81.0
	Rotation Ability	10.0	1.0	10.0	10.0	100.0	6.0	60.0	9.0	90.0	9.0	90.0	2.0	20.0	10.0	100.0	5.0	50.0	9.0	90.0
	Noise Production	10.0	2.0	20.0	3.0	30.0	4.0	40.0	5.0	50.0	3.0	30.0	7.0	70.0	8.0	80.0	7.0	70.0	10.0	100.0
	Apparatus Needed	4.0	4.0	16.0	3.0	12.0	5.0	20.0	4.0	16.0	4.0	16.0	3.0	12.0	6.0	24.0	6.0	24.0	7.0	28.0
	Moment of Inertia	9.0	9.0	81.0	3.0	27.0	2.0	18.0	3.0	27.0	7.0	63.0	8.0	72.0	10.0	90.0	9.0	81.0	9.0	81.0
	Total	51.0	44.0	292.0	35.0	280.0	38.0	267.0	39.0	300.0	41.0	313.0	30.0	243.0	53.0	408.0	53.0	381.0	62.0	464.0
	Score			5.7		5.5		5.2		5.9		6.1		4.8		8.0		7.5		9.1
	Weighted			34.4		32.9		31.4		35.3		36.8		28.6		48.0		44.8		54.6

All matrices have been constructed for technologies based on a literature review of the applied research and brainstorming activities. The results of these decision matrices are given below;

- Laser rangefinder selection: HOKUYO,
- Method of tilting laser beam: Rotate a laser rangefinder at one-axis,
- Motor selection: Brushed DC with encoder and gear and Brushless DC with encoder and gear, Stepper DC,
- Power transfer: Slipring
- Data transfer: IEEE 802.11 (XBee), Slipring.

Each of the above techniques, taken individually, has some difficulties. First one is all these solutions can not be reachable because of budget problems. Second one is none of them presents a complete solution. The use of these results is conducted in Embodiment Design phase.

3.6. Embodiment Design

Embodiment design is the part of the design process. During the embodiment design, concept designs are transformed to final design. The principle solutions at conceptual design phase can be finalized in this section. In this phase all possibilities must be conducted with higher level of information about which devices are going to be used. With embodiment design phase, a conceptual is finalized with subjects which are commonly mentioned below;

- Size,
- Motion,
- Position,
- Material,
- Clearance,

- Installation requirements,
- Main function,
- Component shape,
- Auxiliary function, etc.

3.6.1. Laser Rangefinder Selection

Laser rangefinder selection is concerned around the URG-04LX of HOKUYO. Due to the small measuring range of the scanner, its ability at field of view which is 240° makes it selective. If a larger measuring range or better outdoor performance is necessary, the HOKUYO laser rangefinder should be able to be replaced by a higher performance laser scanner like an IBEO. The advantages of a particularly selected rangefinder are the price which should be kept as small as possible and the availability in the laboratory.

3.6.2. Method of Tilting Laser Beam

Method of tilting laser beam has been selected as rotating a laser rangefinder at one axis. This decision mainly depends on the selected rangefinder, HOKUYO URG-04LX which is suitable for this method. The idea is; the scanning system is provided by rotating laser rangefinder at z-axis in one dimension. Laser rangefinder also measures the distance as the second dimension of the system. Also it rotates the laser beam at another axis which is different from the measuring distance axis and rotary z-axis. In this way, the scanning system has the three dimensional scanning ability. This design allows the scanning platform, continuous scanning capability at three dimension.

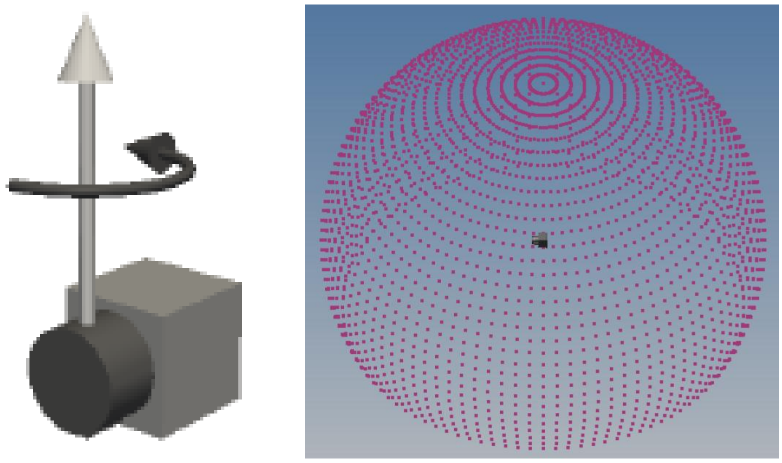

Figure 3.14: Adjustment of Laser Rangefinder

The adjustment of the laser rangefinder is a crucial importance. Laser scanner possesses at a dead angle of 120°. Thus only one meaningful adjustments stands to the selection of laser rangefinder's adjustment. Figure 3.14 shows that, the rangefinder is over the robot, with the dead angle downward arranged. If the rotation takes place around the axis directed upward, then the robot always remains in the dead angle and the highest point intensity is direct over the interested area. This adjustment has the crucial advantage in the comparison over other adjustments, which are mentioned in Chapter 2. The fact that during the measurement the entire range before and behind the robot can be scanned Only points, which are on the ground in the field of dead angle, can't be recognized by robot.

This thesis uses this type of the adjustment, since it corresponds to the requirements better and permits a more efficient structure.

3.6.3. Motor Selection

At motor selection phase, brushed DC motor with encoder and gear has been selected as winner of the decision matrix. Although Step's motor higher torque values, resolution levels, its ease of control methods and efficient position control abilities are better than the brushed DC motor's, by taking account of availability in the laboratory makes step motor usage impossible.

The torque is a crucial criterion. In order to compute the necessary motor torque, it has to be known the moment of inertia of the rotary structure. The needs are its approximate weight and form (moment of inertia). At this time only a rough conception of the dimensions and the weight are presented. The necessary values are taken from conceptual design of rangefinder holder platform which is illustrated in Figure 3.15.

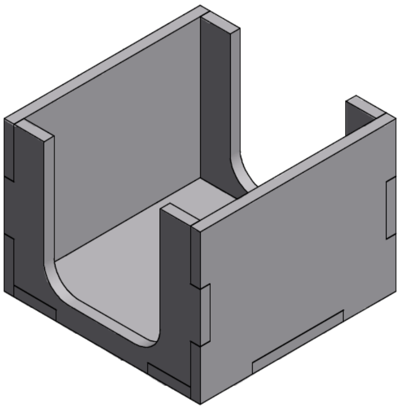

Figure 3.15: HOKUYO Holder

The construction is drawn with the student version by Autodesk Inventor 2011. Properties of Aluminum have been selected from Autodesk Inventor 2011 material library for CAD program calculations and results have been given in Figure 3.16. I_{zz} indicates the moment of inertia value at z-axis which is the rotation axis of scanning platform.

Torque calculation formula is given below:

$$T = I\delta \tag{3.1}$$

where T is the Torque (Nm), I is the Moment of inertia ($kg\,m^2$) and δ is the angular acceleration (rad/s^2).

$$\delta = \Delta w / t \tag{3.2}$$

where w is the angular velocity (rad/s) and t is the time (s).

$$w = (rpm/60)\, x\, 2\pi \tag{3.3}$$

where w is the angular velocity (rad/s).

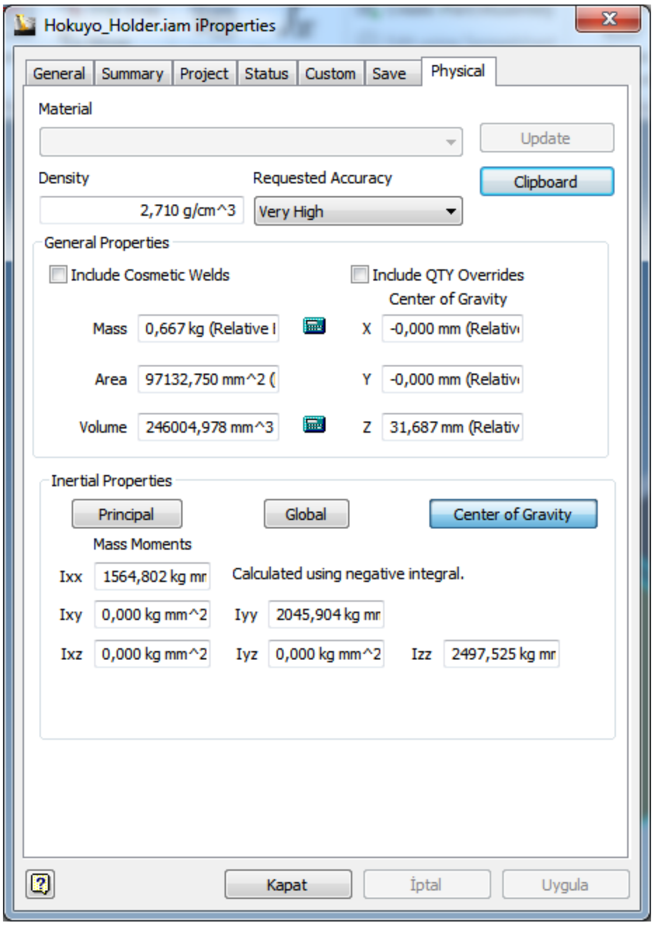

Figure 3.16: Moment of Inertia and Mass Calculation

It is estimated that the scanner mechanism is turned at 500 rpm speed and it reaches this velocity in 0.1 seconds with conceptually designed HOKUYO Holder (Figure 3.15). After the calculations, related motor torque has been calculated as 1.3 Nm if the "HOKUYO Holder" is rotated by direct drive method. The needed torque can be calculated after multiplying this value with a safe factor 2 for taking account of friction forces which are caused by bearings and slipring. After calculations, needed torque value can be estimated to be 2.6 Nm.

Manufacturer Oriantal Motors offers different types of Step Motors. They use closed loop control to maintain positioning operation even during abrupt load fluctuations and accelerations. Properties of Oriantal Motor's step motor (Figure 3.17) given below:

- 0.36° resolution (degree/step),
- Maximum 2 Nm torque,
- 4000 rpm rotation speed,
- Power supply, 24 V_{DC},
- Efficient position control,
- Low heat development,
- Closed loop control system.

As mentioned before, the alternatively selected step motor is not available in the laboratory. Also, high cost of the Oriantal Motor's products is reducing the chance of using this product in this thesis. On the other hand, direct drive method requires the adjustment of the step motor position below the rotary parts by connecting it with a shaft. This adjustment increases the height and weight of the scanning platform.

Figure 3.17: Oriantal Motor Step Motor [20]

The brushed DC Maxon Motor which is available in the laboratory (Figure 3.18) has a gearhead and an encoder at the bottom of the motor.

Figure 3.18: Maxon Motor

Properties of Maxon Motor's DC brushed motor given below:

- Gear reduction rate; 19,
- Encoder Heds 5540, 500 counts per turn,
- 0.31 Nm torque value,
- 450 rpm rotation speed
- Power supply, 24 V_{DC},
- Low heat development.

The Maxon Motor's height is relatively higher than a step motor. It probably makes scanning platform very high and heavy if the direct drive method is used. Another problem is the relatively smaller torque value. Previous calculations show that the required torque level, 2.6 Nm, is not suited with the Maxon Motor. Pulleys and a belt have a chance to solve small torque problem of Maxon Motor. Also, the height of scanning platform is reduced by changing adjustment of motor driving method. The new position of Maxon Motor and rotation method of scanning platform makes Maxon Motor usage possible.

3.6.4. Power Transfer

At power transfer phase, slipring has been selected as winner of the decision matrix which has been illustrated Figure 3.19. Sliprings are used to transfer power to rotating devices such as helicopter rotors, centrifuges, etc. For commercial applications they are suitable to use them in range applications from simple toys to sophisticated medical equipments. There is no loss in data and power when it is rotating. Also, their design allows to use them in a area which is required for splash proof.

In order to guarantee a continuous rotating motion and avoid around rolling the data cable up, a slipring is a right choice. The slipring LPT012-03-03S from the Chinese company, Jinpat Electronics CO., Ltd. fulfills the needs according to manufacturer data, which is mentioned below [21]:

- 3 data (shielded) and 3 power channel,
- 5A current at each circuit channel,
- 0 to 500 rpm operating speed, at both direction,
- Splash proof design.

With the 6 channels, it can be used with the HOKUYO and other rangefinders.. The maximum amperage, which the slipring's per line can transfer, is substantially higher with 5A than the power input of the laser rangefinders.

Figure 3.19: Slipring

3.6.5. Data Transfer

At data transfer phase, IEEE 802.11 has been selected as winner of the decision matrix. For this protocol, XBee, commercially available in markets, is a suitable choice which has been illustrated in Figure 3.21. Its lightweight and small design make this device easy to assemble and suitable for this thesis. On the other hand XBee does not solve the power transfer problem when scanning platform is rotating. Also it's power requirement is another problem. A slipring has to be used for XBee and Hokuyo's power needs. As seen in data transfer decision matrix, XBee is not only solution for data transfer. Another possibility is to use a slipring for both data and power transfer. On the other hand, using a XBee for data transfer instead of slipring, makes extra cost over the designed system. For making a right decision, both choices have to be conducted.

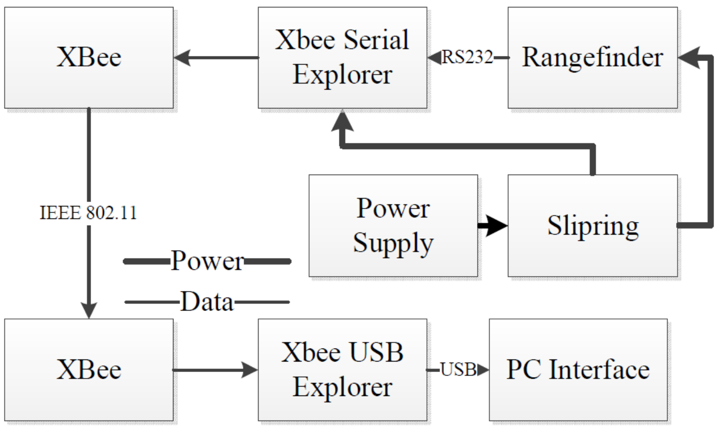

Figure 3.20: Block Diagram of XBee Connection

The block diagram of XBee connection has been given in Figure 3.20. URG-04LX Hokuyo rangefinder sends measured data over RS-232C communication protocol to XBee module. It transfers these data to another XBee module which is connected to PC over usb. URG 04LX Hokuyo rangefinder sending distance data packages at 10 Hz with size of 683 bytes. After several experimental tries, it has been understood that these data packages make XBee module overload and the module cuts the wireless connection. It must be reconnected to continue data transfer. The successful connection time between XBee modules is changing from 2 seconds to 10 seconds and it is not regular. Even with regular use of short term connection, this limited connection time is not enough to use XBee module for continues scanning.

Figure 3.21: XBee and Explorer Modules

On the other hand, there are several experimental works which are succeeded at data transferring over XBee module in the literature. [42] is mainly concerned about Micro Air Vehicles which have to react quickly to their dynamic environments. 2.4 GHz XBee communication module connects with ground pc and responsible for sending local image samples, taken by the Micro Air Vehicle's camera processor. [43] shows an another experimental work, using XBee module for transferring processed image data over wireless communication. The image sensor connects pc interface and pc interface connects to XBee module. Another XBee receiving platform receives the data and in turn sends data to the main controller. Both literature researches show that XBee module can be successfully used for transferring data when modules connected to related devices' processors. In our experimental setup, HOKUYO directly connects XBee module without any preprocessor over RS-232C connection protocol and receiver XBee module connects with USB to pc interface. The processor, inside of the HOKUYO, can't recognize the XBee module over USB. RS-232C connection protocol is necessary to obtain HOKUYO's distance data. Because of this, XBee module, supporting RS-232C, connection protocol has been used for connecting HOKUYO rangefinder. By taking account of these situations, it can be possible to overcome the connection problem. But the connection problem between XBee modules when transferring distance data packages hasn't been solved and the problem continues. This problem forces usage of slipring as data transfer method in this thesis.

Despite the lost data of XBee communication, slipring works well with same set up without lost. After numerous failures when transferring HOKUYO's distance data packages over XBee modules, it has been decided to use a slipring for data transfer.

3.6.6. Arrangement of Physical Elements to Carry out Function

After the movement and the adjustment of the laser rangefinder are decided, the construction of the structure can be tackled. Since it concerns a mobile system, all basic design features from aluminum are manufactured.

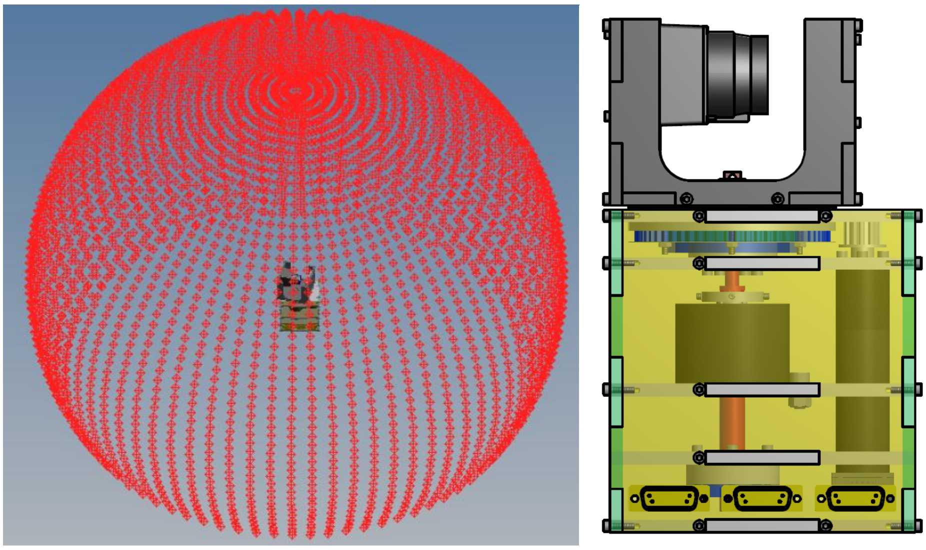

Figure 3.22: Construction of 3D Scanning Platform

The field of view is represented with red dots in Figure 3.22. It shows volume of the 3D depth data, with the dead angle of 120°, directed downward. Maxon Motor is adjusted the right hand side of the rotary part to decrease height of the scanning platform.

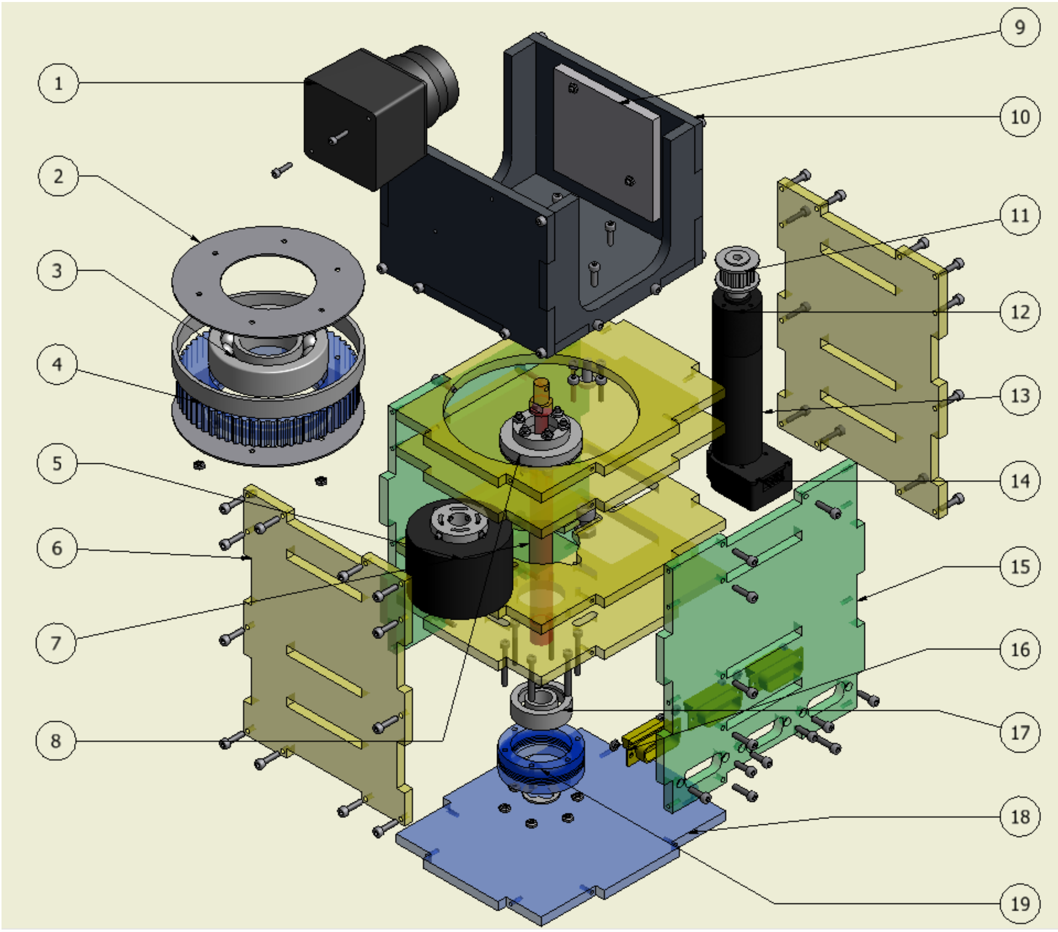

Figure 3.23: Construction of the 3D Scanning Platform

The exploded construction is shown in Figure 3.23. Some of the most important components of the system can be summarized with numbers as:

1. Hokuyo URG-04LX laser rangefinder,
2. Upper bearing support,
3. FAG 6206 bearing,
4. Timing belt pulley, 60 teeth, T5 step,
5. Slipring,
6. Main supporter plate right and left sides,
7. Shaft mile,
8. Supporter of upper bearing,
9. Balance weight,

10. Hokuyo holder assembly
11. Timing pulley, 12 teeth, T5 step,
12. Gear head,
13. Maxon Motor, DC brushed,
14. Encoder, Head 5540,
15. Main supporter plate of front side,
16. d-sub 15 pin connector,
17. FAG 6201 bearing,
18. Basement plate,
19. Supporter of bottom bearing.

The structure consists of installed parts and a rotary part (10), which the laser rangefinder (1) carries. The laser rangefinder is attached at the center of the scan range is exactly on the extension of the rotation axis. The construction of the being certain part consists of four vertical supports, to which four levels are fastened. The lowest parts hold a bearing and a slipring, the middle part holds a brushed DC Maxon Motor and a bearing (3). By exchange of the base plate, it can be easily adapted the structure on any robot platform.

This adjustment makes pulleys and a belt usage possible. Also this design reduces the required torque level. Pulley and belt types and sizes are very limited in markets. Another design problem is finding a suitable pulley and belt combination and their adjustment to the scanning platform. After some investigation, pulleys are found in different sizes which are suitable for usage of timing belt. Using timing belt makes a direct connection between Maxon Motor's encoder and rotary parts of scanning platform. Encoder's position data can be used for detection of rotary parts position after multiplying with Maxon Motor's gear head and pulley's reduction rate. Maxon Motor's and pulley's reduction rates are respectively 19 and 5. It reduces the rpm value of maxon motor which is about 450. Unfortunately Maxon Motor's rpm reduces to 450 to 90 because of pulleys reduction rate. On the other hand using a gear head increases torque value which is about 0.31 Nm. After calculating with the suitable pulley's moment arms, required torque value decreases 2.6 Nm to 0.5 Nm which is relatively higher than the torque value of DC brushed Maxon Motor. The required torque level recalculated after pulley's reduction rate for 90 rpm with safety factor 2 and the result is 0.47 Nm. Values (0.47 Nm and 0.31 Nm) are near enough to rotate scanning platform in a 0.1 seconds to 90 rpm by taking account of safety factor 2.

This scanning platform fulfills some objectives by this design. These objectives have been given below:

- Scanning ability at 3D: The construction has HOKUYO rangefinder sensor which is scanning the environment in 2D at one-axis (rotating with 120° dead scanning angle) and one-axis (distance measurement-depth). Also HOKUYO sensor is being rotated by brushed DC motor at one-axis. So the scanning platform has a 3D scanning ability which is illustrated in Figure 3.22,
- Capability of higher rotation angle: 360° scanning angle has been done by construction design,
- Capability of higher scanning frequency, (scanning speed).: HOKUYO's scanning speed is 100 msec/scan and brushed DC Maxon Motor has a ability of 450 rpm but this speed reduces 5 times because of pulleys' reduction rate. Despite of this relatively low rpm, with today's technology it is still hard for data acquisition and processing. The slipring rotation speed is offered 500 rpm by manufacturer. If higher rotation speed is necessary for a short time, which is need for a very fast scanning, slipring can be operated if the Maxon Motor is changed with faster one. But higher rotation speeds decreases slipring life-time according to manufacturer,
- Ability of selecting field of view. Slipring and brushed DC motor can be driven at both directions (clockwise and counter-clockwise at any speed). User can select related interested area for scanning.

With the antifriction bearing, single row deep groove ball bearings are selected. To obtain low resistance as possible, when the scanning platform is rotating, same type of bearings have been adjusted at rotation axis. And they are connected and aligned to each other with a rotary shaft. The axial and radial forces which are caused by rotation forces are handled by bearings. Single row deep groove ball bearings are commonly used under radial forces. Some axial forces come out when scanning platform is rotating. Investigations show that at limited force levels, axial forces can be handled by single row deep groove ball bearings. Unfortunately there is no available information about acceptable axial force levels. Angular contact bearings are especially designed for working under axial loads. In addition to the axial forces, radial forces can be handled by angular contact bearings. The disadvantages of using this type of bearings are higher radial space and requirement of minimum axial load. Radial space is an important design factor for balanced design of scanning platform. After considering the low axial forces at scanning platform and taking account of the requirement of minimum radial space single row deep groove ball bearings have been selected. 6201 and 6206 series single row deep groove ball bearings have been selected for this thesis from Manufacturer FAG. Their allowable rotation speeds are much higher than the expected rotation speed of scanning platform. The quality of FAG Manufacturer bearings make bearing’s life time longer and good enough to use in this thesis.

3.7. Detail Design

This phase is the last phase of design process. The construction is drawn with the student version by Autodesk Inventor 2011 and the general dimensions of construction, exploded views and bill of material list can be found in Appendix A.

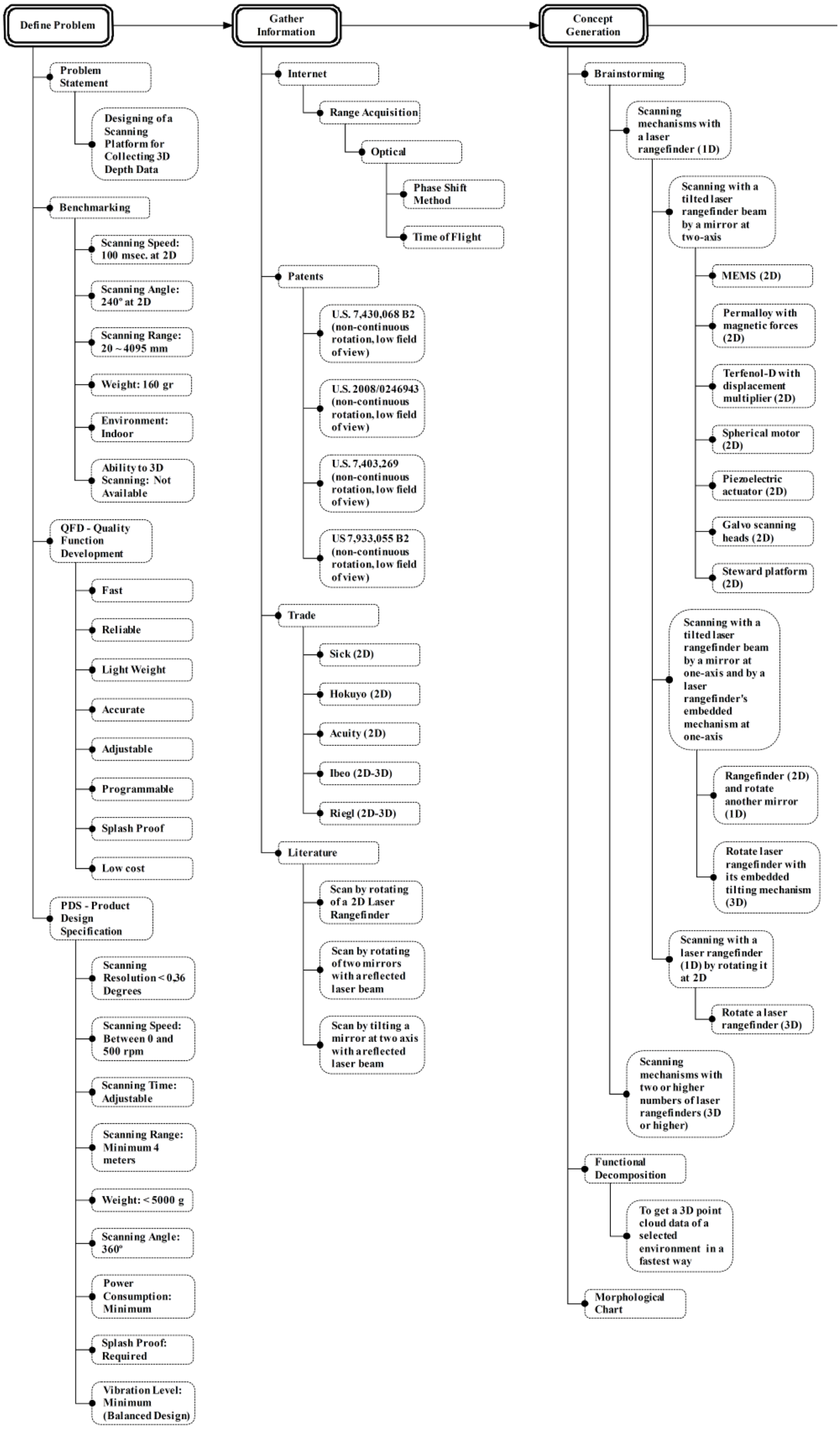

Figure 3.24: Steps in Engineering Design - 1

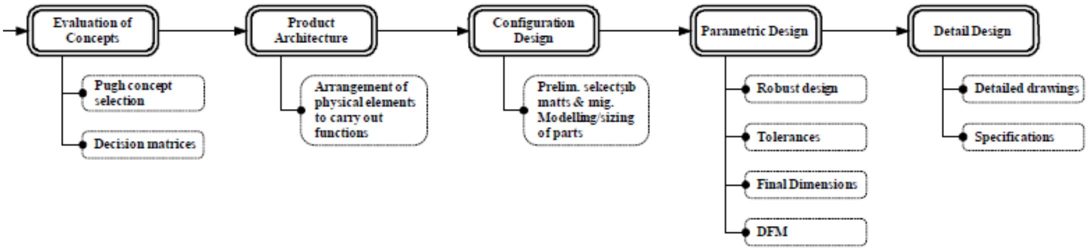

Figure 3.25: Steps in Engineering Design – 2

3.8. Summary of System Design

In evaluation, system design from define a problem to detail design has been completed. Until now, problem has been defined, all information about system design has been gathered, conceptual design phase has been completed and a morphological chart and decision matrices have been evaluated. With respect to these completed phases, embodiment design phase has been started. All suitable devices have been selected by taking account of decision matrix results. After finalize the embodiment design phase detailed design have been done.

This chapter successfully demonstrates the system design phase. Next chapter is conducted about implementation of scanning platform.

CHAPTER 4

IMPLEMENTATION OF SCANNING PLATFORM

4.1. Electrical Connection Diagrams

Before giving the experimental results of the scanning platform, it is helpful to understand the connection diagram of designed system (Figure 4.1).

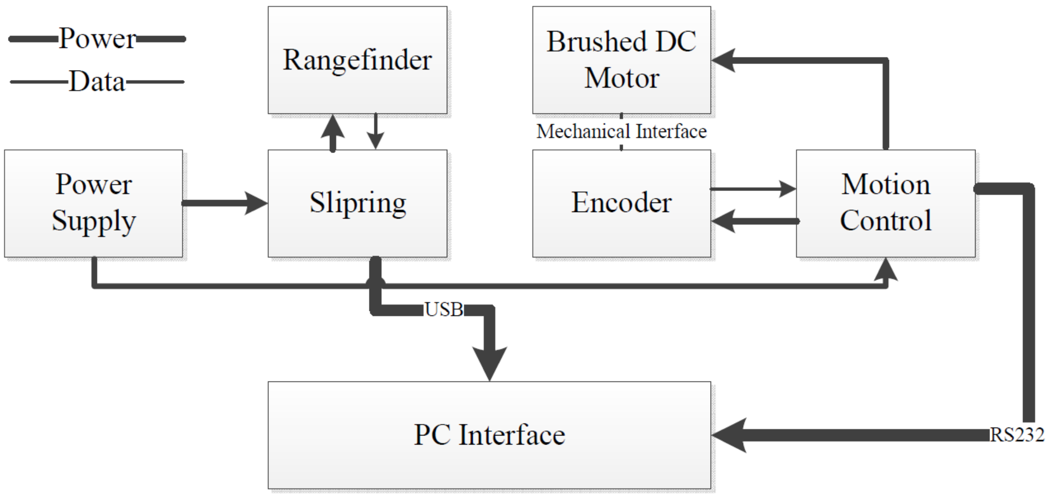

Figure 4.1: Schematic of Connection Diagram

URG-04LX HOKUYO rangefinder is connected to PC interface with a USB connector. Also, its needed power is transferred by the help of slipring. To guarantee a continuous data and power transfer when the platform is rotating the slipring has been placed between PC interface and rangefinder. Faulhaber drive system is also connected to PC interface. Faulhaber is driving brushed DC motor with a help of potentiometer. In addition to driving ability of Faulhaber, it is also getting encoder's position data and transferring it to PC interface. PC Interface, running under Linux Ubuntu, is processing HOKUYO's distance and encoder's position data. Distance data is transformed by spherical coordinates to Cartesian coordinates with taking account of the position data which is provided by encoder. This transformation method has been conducted at section 4.5 Plotting Control Environment.

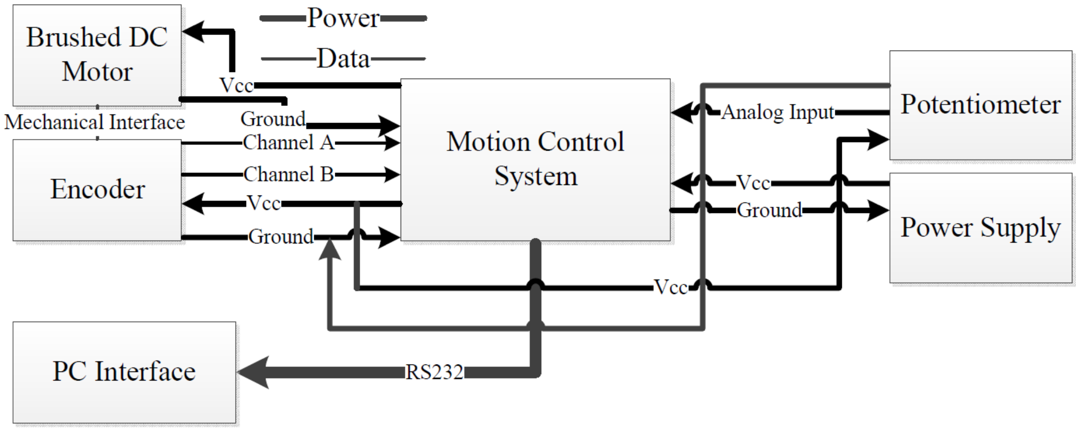

Figure 4.2: Schematic of Connection Diagram (Motion Control System)

Faulhaber MCDC 3003/06 S Series Motion Control System is used for driving brushed DC motor and reading the encoder's position data (Figure 4.2).

Faulhaber Motion Control System is to operate as a voltage regulator by setting it's mode "Voltage Regulator Mode". In order to achieve this 10 kΩ potentiometer has been coupled with the control system. Hence the brushed DC motor can be able to controller in a voltage range of 0 to 5V.

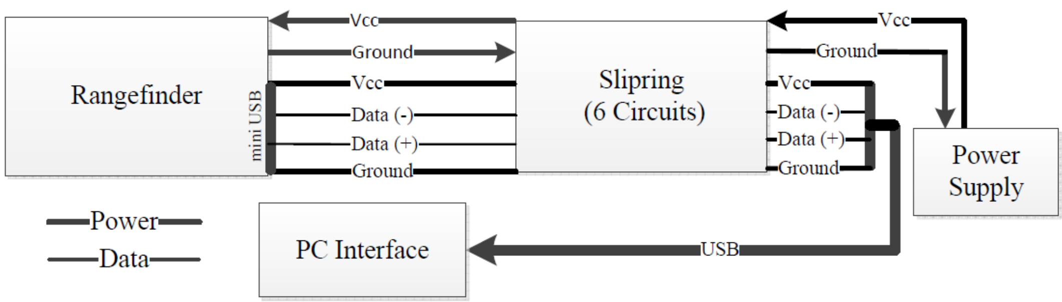

Figure 4.3: Schematic of Connection Diagram (Rangefinder)

Connection diagram of HOKUYO URG-04LX rangefinder has been illustrated in Figure 4.3. Slipring has 6 circuits for transferring data and power when the scanning platform is rotating. Standard USB connector is providing related connection between PC interface and rangefinder. Electrical architecture of scanning platform has been given in Appendix B.

4.2. Data Acquisition

Distance data packages of rangefinder and encoder position data are acquired by the help of open source Robot Operating System (ROS), hosted on an Ubuntu Linux based processor.

Laser rangefinder URG-04LX of HOKUYO is capable of 10 scans per second since every 2D scan is accomplished within 100 msec. However, the actual data acquisition is accomplished within 67 msec. The end of the actual scan is signaled by a synchronous output which is synchronized with scanning and produces a single pulse for approximately 12.5msec. As a matter of fact Figure 4.4 is based on the signal timing of the URG-04LX.

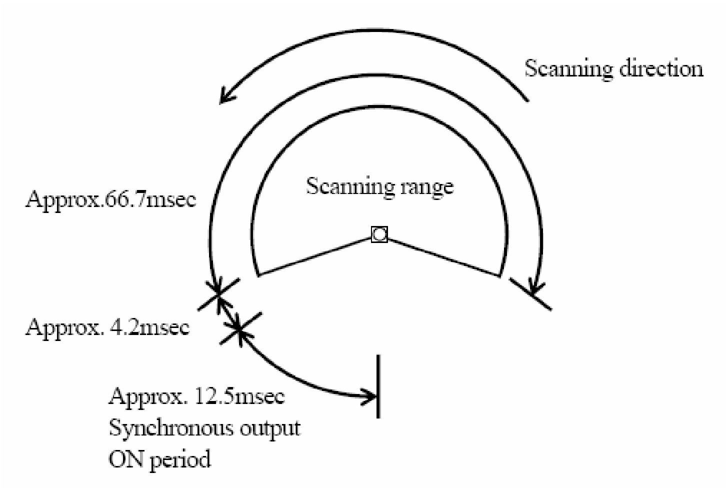

Figure 4.4: Scanning Time [10]

To succeed at synchronized data acquisition, which is between laser rangefinder URG-04LX of HOKUYO and encoder position data, timing of data requests have been constructed and illustrated in Figure 4.5.

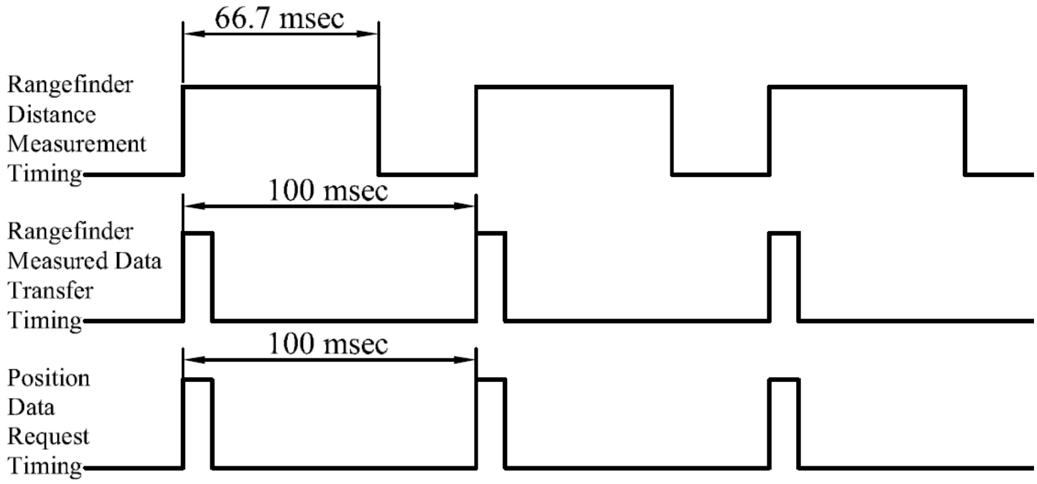

Figure 4.5: Timing Diagram of Data Acquisition

Laser rangefinder completes its range scanning for 240º in 66.7 msec. But it sends data packages to pc with 100 msec time periods. For synchronization, ROS requests the position data of encoder for every 100 msec. It has been assumed that rangefinder scans the environment for 100 msec. 1º angular rotation has been equally divided into 683 pieces which is the number of distance data inside of the data package, sent by HOKUYO. This approach defines the position of distance data in 3D environment.

4.2.1. HOKUYO Rangefinder Data Acquisition

According to [40], “hokuyo_node” is a driver for SCIP 2.0 compliant HOKUYO laser rangefinders. The driver has ability to support some SCIP 1.0 compliant range-finders such as the URG-04LX which is used in this thesis. Source code of “hokuyo_node” is given in [41]. By using of this source code method of getting scanned data and other additional information are given in [40].

4.2.2. Reading Angular Rotation of the Platform

As shown in Figure 4.2, the encoder of DC brushed motor is connected to motion control system. In this connection, Channel A, Channel B, Ground and Vcc are used. The motion control system is used as an encoder reading board. It is possible to read encoder data from Faulhaber Motor Control System via serial channel.

4.3. Manufacturing Method for Scanning Platform

All parts of scanning platform (except shaft mile) have been manufactured from 5075 series aluminum alloy to reduce the weight and withstand the corrosion effects of environment. Another reason for this selection is about the material's easy maintainable properties. All parts are suitable for laser cutting method. Comparing with other kinds of forming methods, laser cutting has the advantages of small cutting slit, smooth cutting edge, little heat distortion, no need other cutting tools and so on. Shaft mile's material has been selected as stainless steel. The geometry of mile requires the usage of standard turning machine. Bolts are locked with Loctite to prevent unwanted disassembly.

4.4. Manufactured 3D Scanning Platform and Control Environment

Embodiment design is the part of the design process. During the embodiment design, concept designs are transformed to final design. The principle solutions at conceptual design phase can be finalized in this section. In this phase all possibilities must be conducted with higher level of information about which devices are going to be used. With embodiment design phase, a conceptual is finalized with subjects which are commonly mentioned below;

Figure 4.6: 3D Scanning Platform

To validate the use of a laser rangefinder and other physical elements during rotation progress, manufacturing of scanning laser platform and assembly of physical elements have been done (Figure 4.6).Weight of scanning platform is less than 5000 g. 60cmx60cmx60cm cubic control environment is manufactured with ±2 cm tolerance value for each side (Figure 4.7).

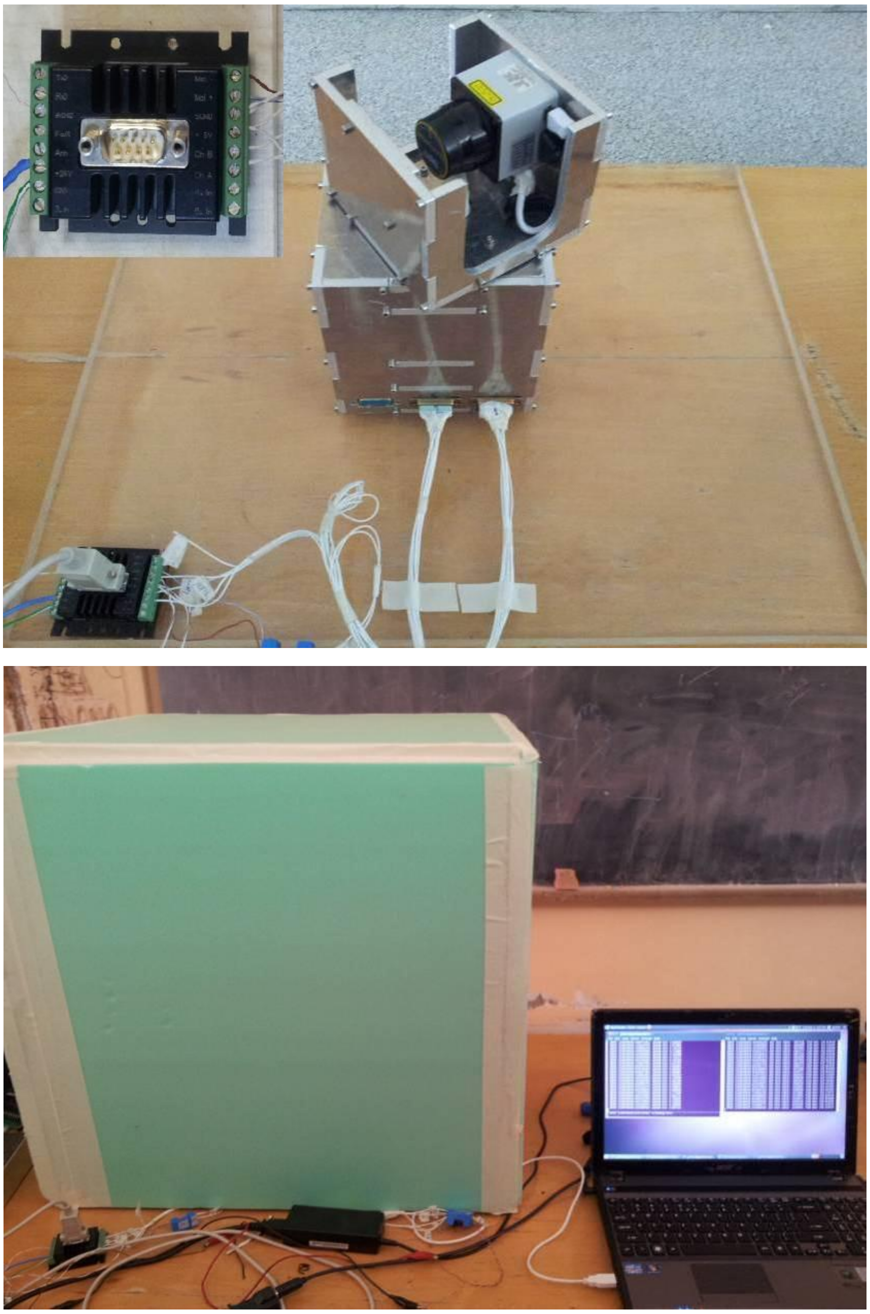

Figure 4.7: Control Environment

4.5. Plotting Control Environment

The points, provided by HOKUYO, are in one plane. It is possible to translate these spherical coordinates into Cartesian coordinates. By this way this data is represented in a 2D frame of reference with its origin in the HOKUYO sensor.

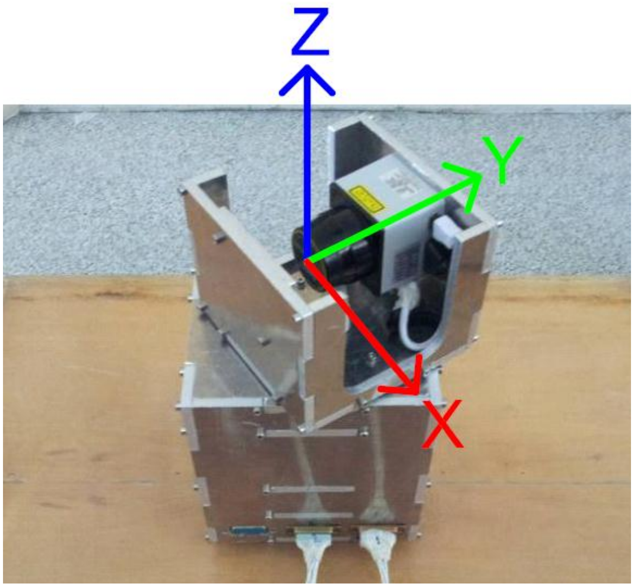

Figure 4.8: Orientation of Cartesian Coordinate System

Orientation of Cartesian coordinate system has been given in Figure 4.8. The equations for the transformation by spherical coordinates (ri,αi) to Cartesian coordinates (xi,zi) are given below:

$$x_i = r_i . \cos \alpha \quad (4.1)$$

$$z_i = r_i . \sin \alpha \quad (4.2)$$

where r is the distance value which is sent from HOKUYO (mm) and α is the Angle of HOKUYO's Laser Beam (radian).

The angle β is provided by converting data from data which is sent by encoder. Eq. (4.3), Eq. (4.4) and Eq. (4.5) can be used to transform a 3D point in spherical coordinates into Cartesian coordinates which are given below:

$$x_i = r_i . \cos\alpha . \cos\beta \tag{4.3}$$

$$y_i = r_i . \cos\alpha . \sin\beta \tag{4.4}$$

$$z_i = r_i . sin\alpha \tag{4.5}$$

where β is the rotation angle of scanning platform (radian).

As an example of data acquisition for a 3D point cloud, it is used a box which is mentioned in section 4.4 Manufactured 3D Scanning Platform and Control Environment.

Box’s center and HOKUYO rangefinder’s rotation center are as aligned as possible. The resulting 3D point cloud has been illustrated in Figure 4.9.

Figure 4.9 shows that physical elements of 3D scanning platform, slipring, rangefinder, motor and it’s components, are working well. There is no data loss at slipring when it is rotating. By plotting acquired data implementation of scanning platform has been completed successfully.

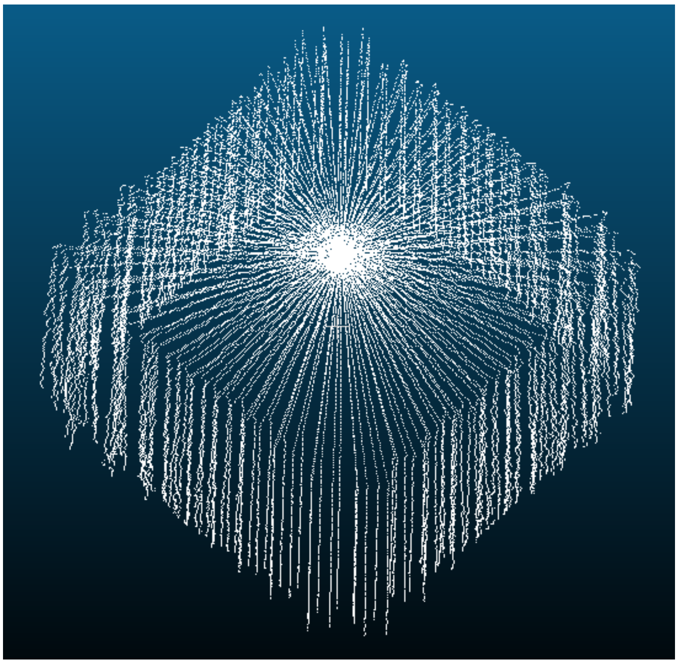

Figure 4.9: Plotted 3D Point Cloud Data of Controlled Environment

Even though in this thesis is not interested in the processing of the 3D point cloud some remarks can be made. There are some errors at the edges. The points are not aligned very well. Some correlation methods can be used to fix these errors as a future work. Also, it must be taken account of URG-04LX HOKUYO rangefinder's accuracy value which is ±10 mm between 20 mm and 1000 mm.

Figure 4.10: Non-Controlled Environment and Plotted 3D Point Cloud Data

As an another example; non-controlled environment has been scanned and plotted with appropriate program and it has been shown in Figure 4.10. There are some errors on plotted data which has been clearly seen at bottom right of the figure. The reason of this error mainly depends on the assumption which is mentioned in section 4.2 Data Acquisition. This assumption causes the position assignment error of measured distance data. Extra reflections, caused by the corners of the scanned environment, effect the distance calculation which is done by HOKUYO. Another important factor is rangefinder's accuracy value which is ±%1 of measured data between 1000 mm and 4000 mm. Also, there are lots of objects which have un-regular geometry make scanned 3D depth data distorted.

4.5.1. Configuration and MATLAB Code for Cartesian Coordinates Translation

As mentioned in section 4.5 Plotting Control Environment, HOKUYO URG-04LX rangefinder sends measured distance data packages in 0.1 second as 683 bytes. Encoder reads the position data of scanning platform. The scanning platform has been set to complete a 360° rotation in 3.6 seconds. The code is looking for the encoder data for each 0.1 second and calculates the position of rotating platform. Eq. (4.3), Eq. (4.4) and Eq. (4.5) are used by the MATLAB code which is given in Appendix D to create 3D point cloud data.

4.6. Analysis of Plotted Control Environment

Laser rangefinder URG-04LX of HOKUYO measures distance with accuracy of ±10 mm. In addition to error which is cause by accuracy, some errors come from Cartesian coordinate translation formula and extra reflections caused by edges of the box. By taking account of these errors into consideration, some analysis have been done to confirm the error distribution.

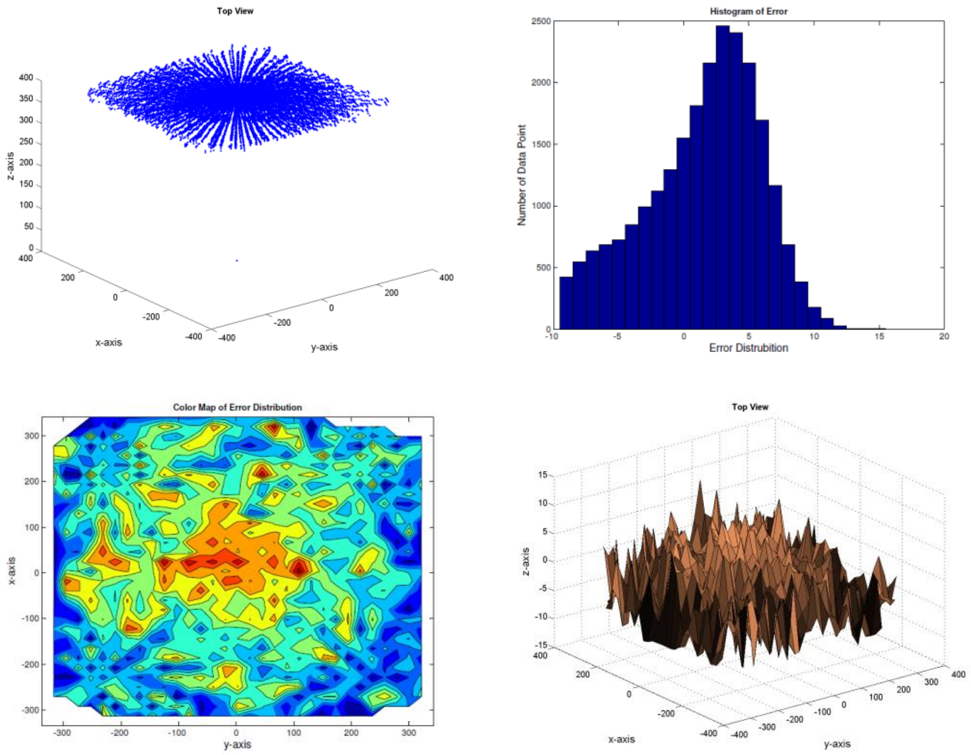

Figure 4.11: Analysis of Top Surface

Analysis figures of top surface have been given in Figure 4.11. Depending on the error distribution figure, most of the acquired data is between -10 mm and +10 mm as expected. The number of data, which is not inside of rangefinder accuracy value, is relatively small but the reason of this mainly depends on assumption which is mentioned in section 4.2 Data Acquisition. The meshed data has been plotted and homogenous data distribution, between -10 mm and +10 mm can be seen in figure of it.

Color mapped figure shows that, there are some data distortions at the center of plotted data. It can be explained by density of scanned data which is higher than farther distances from the center.

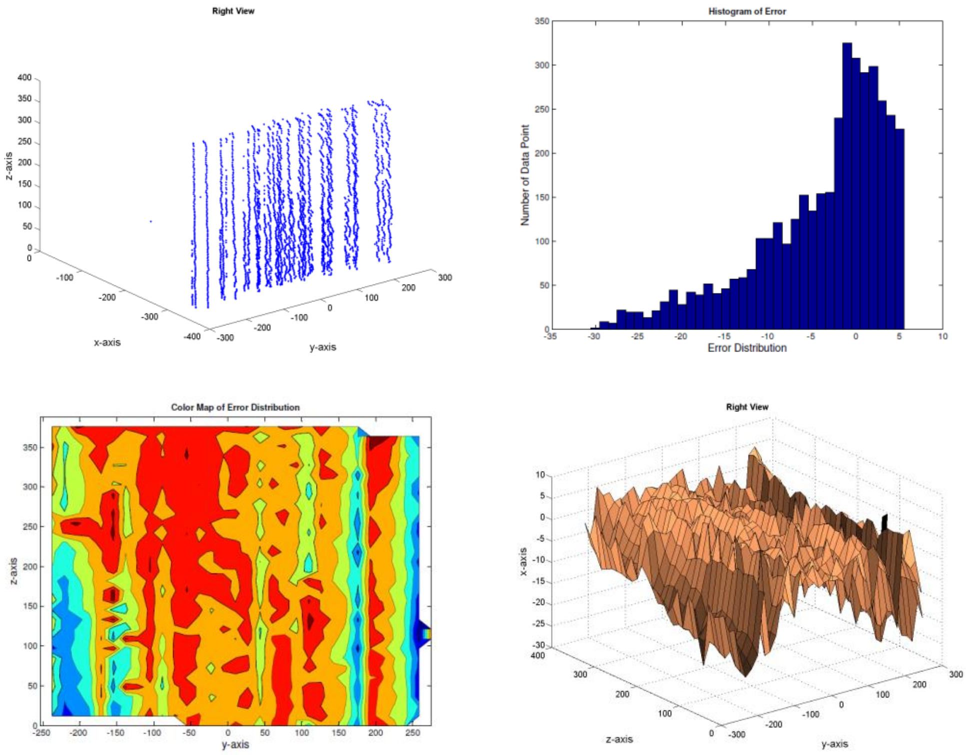

Figure 4.12: Analysis of Right Surface

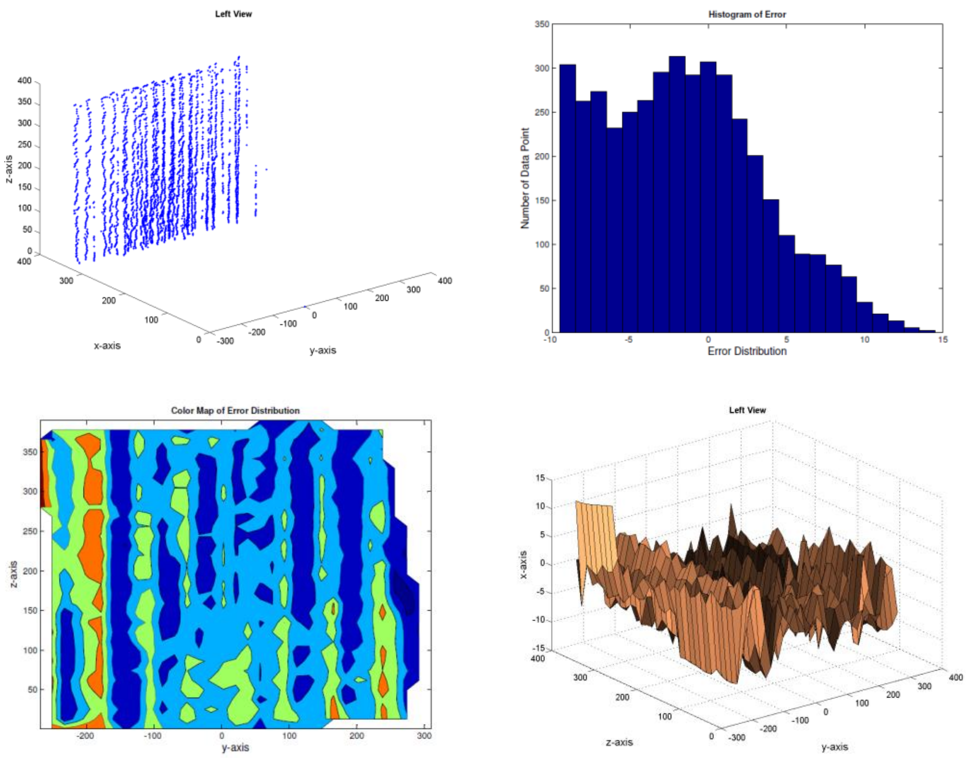

Figure 4.13: Analysis of Left Surface

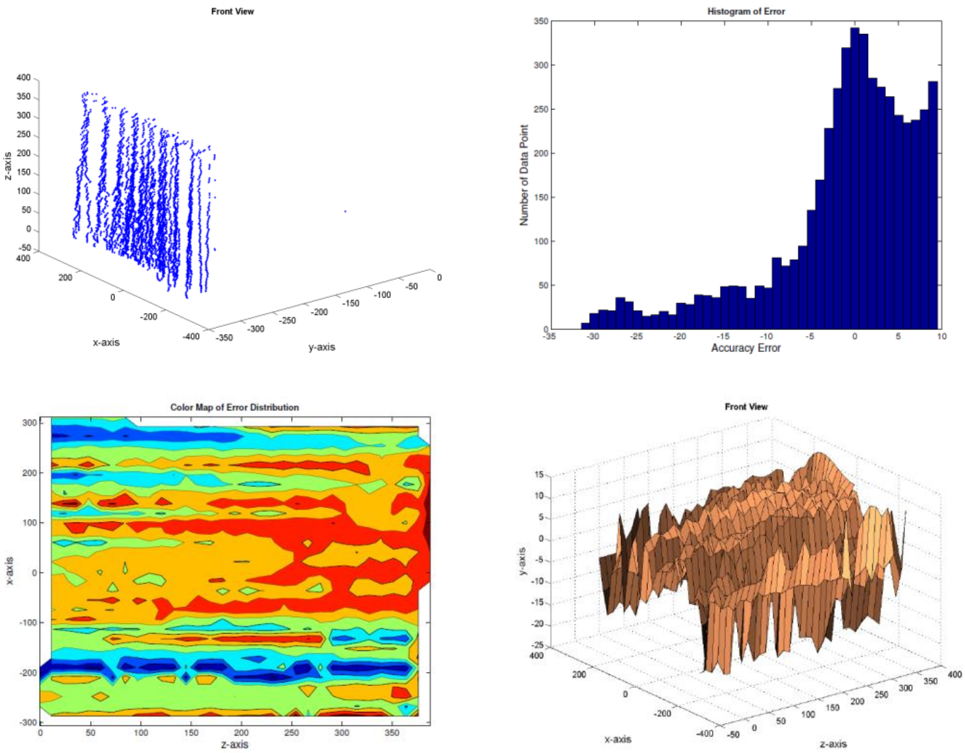

Figure 4.14: Analysis of Front Surface

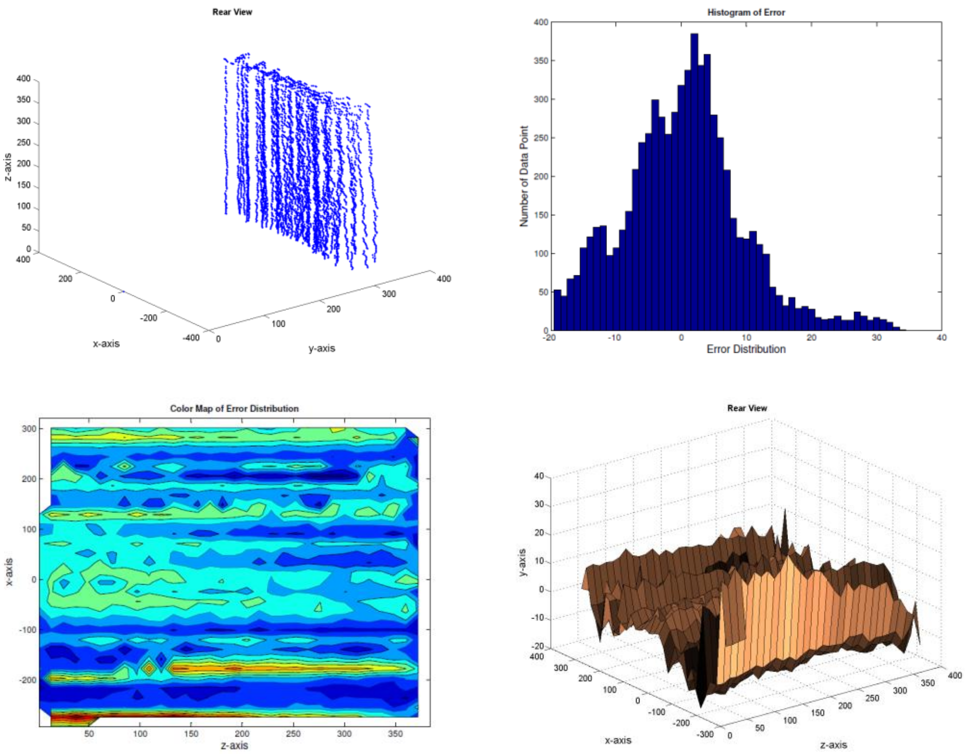

Figure 4.15: Analysis of Rear Surface

Analysis figures of other surfaces have been given in Figure 4.12, Figure 4.13, Figure 4.14 and Figure 4.15. Depending on the error distribution figures, most of the acquired data is between -10 mm and +10 mm as expected. The number of data, which is not inside of rangefinder accuracy value, is relatively small but the reason of this mainly depends on assumption which is mentioned in section 4.2 Data Acquisition.

Color mapped figures show that, most of the distorted data has been seen right and front surfaces. These surfaces' plotted lines haven't been aligned well. This situation increases the error distribution.

All analysis clearly shows that most of the 3D point cloud data is located between -10 mm and +10 mm which is the HOKUYO rangefinder's accuracy value. It is good enough to react correctly for a robotic platform.

CHAPTER 5

CONCLUSIONS AND FUTURE WORKS

5.1. Conclusions

In the context of this thesis, a system which is using 2D laser rangefinder is developed with the rotation of the laser scanner around the vertical axis. The position and adjustment of the scanner are selected in such a way, the fact that it can completely measure the environment with half rotation.

The interface of DC brushed motor allows controlling the rotation, with a maximum number of 190000 encoder pulses, between 0º to 360º. On the other hand, the interface of laser rangefinder also allows controlling HOKUYO's angular resolution at 0.36° per step. These resolution values are sufficient and higher when 3D scanning platform is compared with other 3D scanning solutions. Also it has 360° scanning capability at high resolution and 500 rpm with a faster motor. Half rotation may reduce to scanning time half of it.

The system is developed for a laser rangefinder with relatively small range and can be optimized for the employment on a robot platform. The measured values can be converted directly by the system into Cartesian and polar coordinates for example the map production and/or the development of way identification algorithms.

Some critical parts of scanning platform, HOKUYO, slipring and d-sub connectors, have been selected as splash proof. Also, the construction has been designed to prevent possible liquid leakage in case of any liquid splash. Because of expensive electronic parts and high risk, it hasn't tested under real conditions.

Owing to the construction from aluminum, with a low weight and relatively small dimensions is reached the possibility of a simple adaptation on the robot platforms. The system can be adapted by exchange of the base plate to almost any robot platform.

Modularity is pointed out with the exchange of the laser rangefinder by one which is at higher range. Designing of construction shows that the system is suitable for this employment in principle also.

The system offers sufficient place for extensions, then further laser rangefinders and cameras in many places at the structure can be installed. The price is very low from commercial systems. It also offers more qualified data from other systems.

5.2. Future Work

In the context of this work for temporal reason, all visions and improvements are not been converted, in order to give an overview of the possible future progress of the system, some further works has been given below:

- Finite element analysis of all structure members,
- Vibration analysis of assembled parts,
- Research of alternative rotary translation systems,
- For mass production optimizing system needs and reducing cost and weight,
- Improvement of data registration,
- Develop a better scanning platform with a more powerful motor (higher rpm and torque values) and a better rangefinder (higher range measurement capability, indoor/outdoor).

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APPENDIX A

DETAILS OF SCANNING PLATFORM

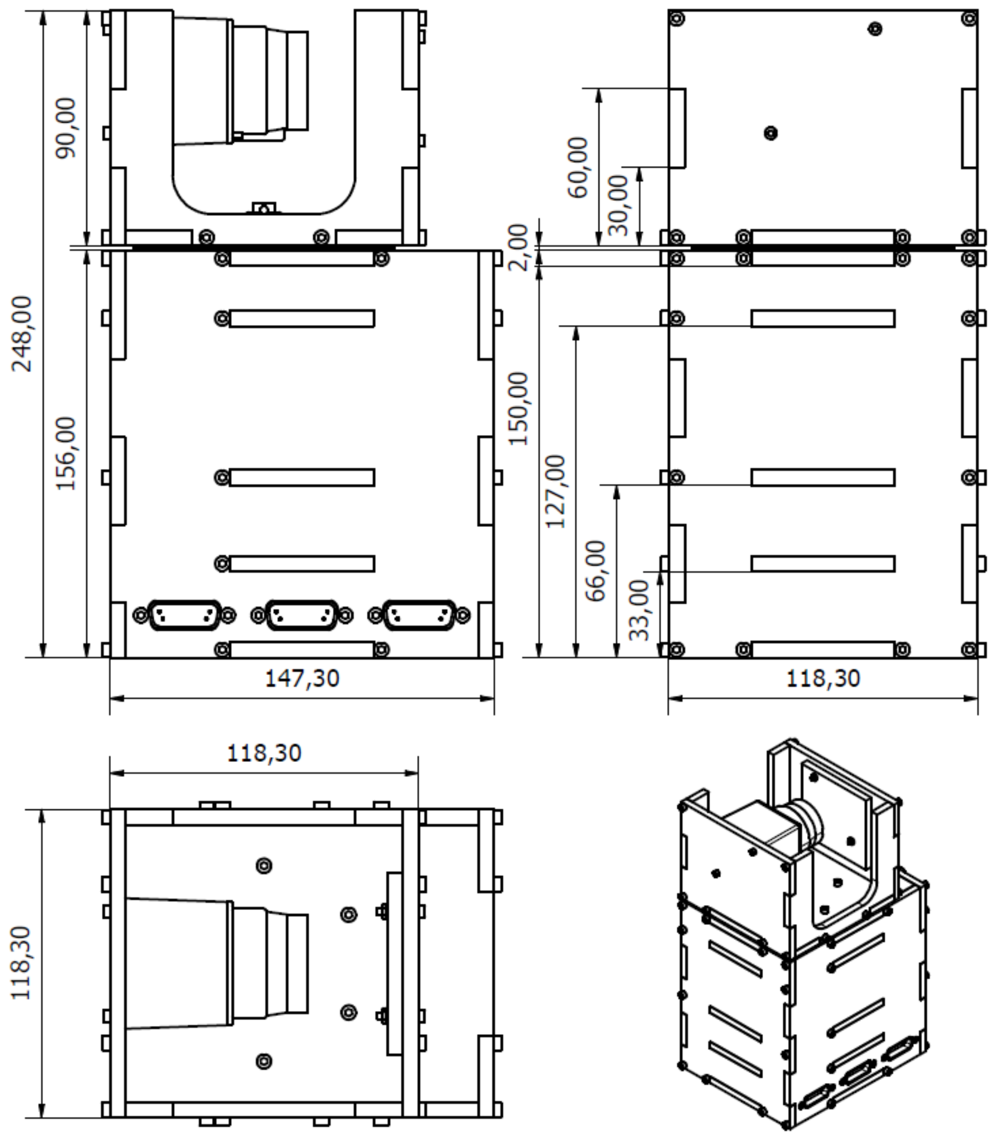

Figure A.1: General Dimensions of 3D Scanning Platform

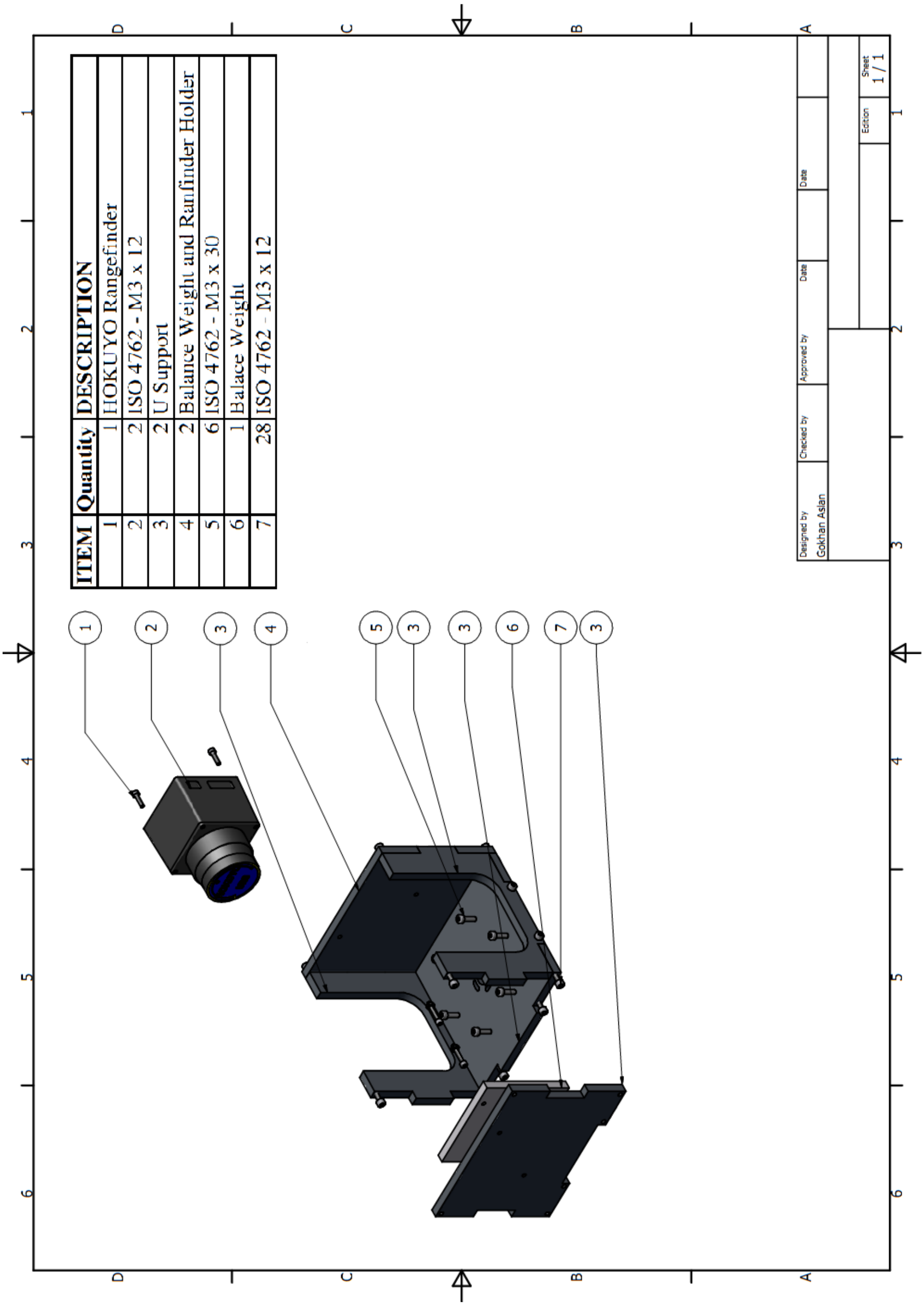

Figure A.2: Hokuyo Holder Assembly

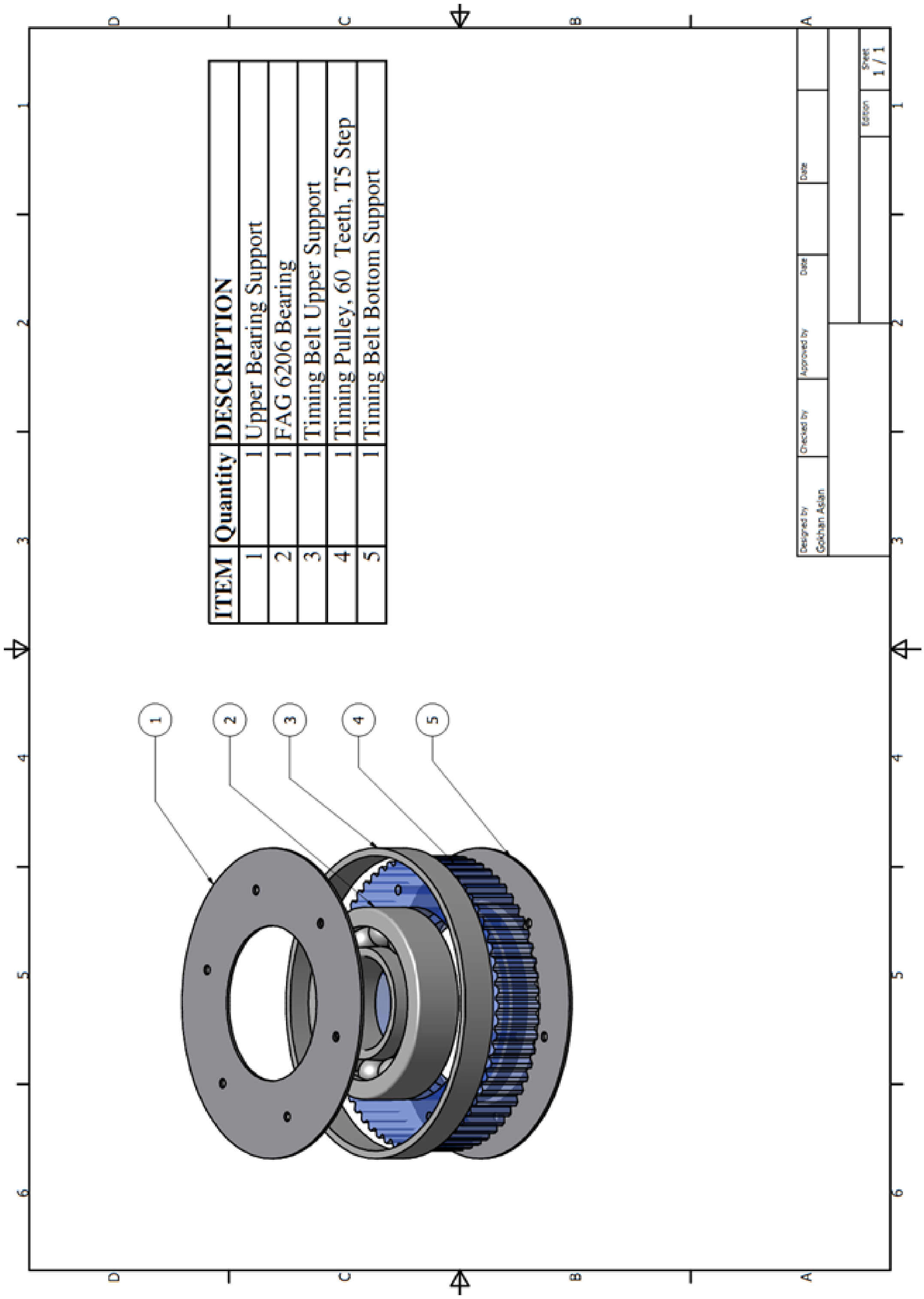

Figure A.3: Timing Pulley Assembly

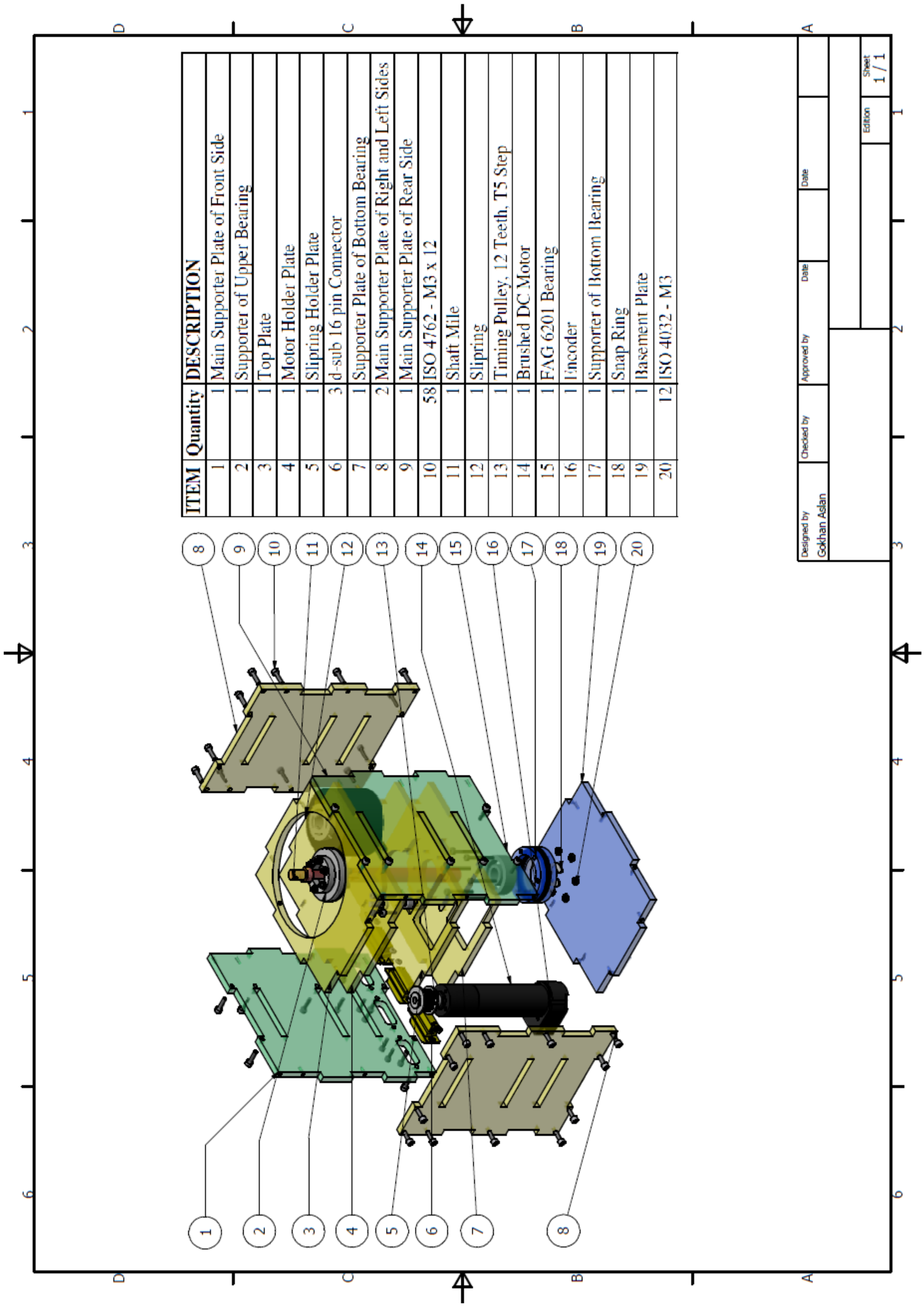

Figure A.4: Basement of Scanning Platform Assembly

Bill of material list has been given below:

Table A.1: Bill of Material List

ITEM	QTY	DESCRIPTION	MATERIAL
1	1	Main Supporter Plate of Front Side	Aluminum
2	1	Main Supporter Plate of Rear Side	Aluminum
3	1	Upper Bearing Support	Aluminum
4	1	Timing Pulley, 12 Teeth, T5 Step	Aluminum
5	1	Timing Pulley, 60 Teeth, T5 Step	Aluminum
6	1	Hokuyo Holder Assembly	Aluminum
7	1	Timing Belt Bottom Support	Aluminum
8	1	Top Plate	Aluminum
9	1	Supporter of Upper Bearing	Aluminum
10	1	Slipring Holder Plate	Aluminum
11	2	Main Supporter Plate of Sides	Aluminum
12	1	Supporter Plate of Bottom Bearing	Aluminum
13	1	Basement Plate	Aluminum
14	1	Supporter of Bottom Bearing	Aluminum
15	1	Shaft Mile	Stainless Steel
16	1	Snap Ring	Steel
17	1	Balance Weight	Aluminum
18	62	ISO 4762 - M3 x 12	Stainless Steel
19	2	ISO 4762 - M2,5 x 16	Stainless Steel
20	2	ISO 4762 - M2,5 x 10	Stainless Steel
21	2	ISO 4762 - M2,5	Stainless Steel
22	6	ISO 4762 - M3 x 30	Stainless Steel
23	1	ISO 4762 - M8	Stainless Steel
24	12	ISO 4762 - M3 x 25	Stainless Steel
25	1	ISO 4762 - M6 x 12	Stainless Steel
26	1	ISO 4762 - M6	Stainless Steel
27	6	ISO 4762 - M3 x 10	Stainless Steel
28	24	ISO 4762 - M3	Stainless Steel
29	1	Pin	Stainless Steel
30	1	FAG 6201 Bearing	Steel
31	1	FAG 6206 Bearing	Steel
32	3	d-sub 15-pin connector	-
33	1	Brushed DC Motor	-
34	1	Rangefinder	-
35	1	Slipring	-

APPENDIX B

ELECTRICAL CONNECTION DIAGRAM

Detailed electrical connection diagram has been given below:

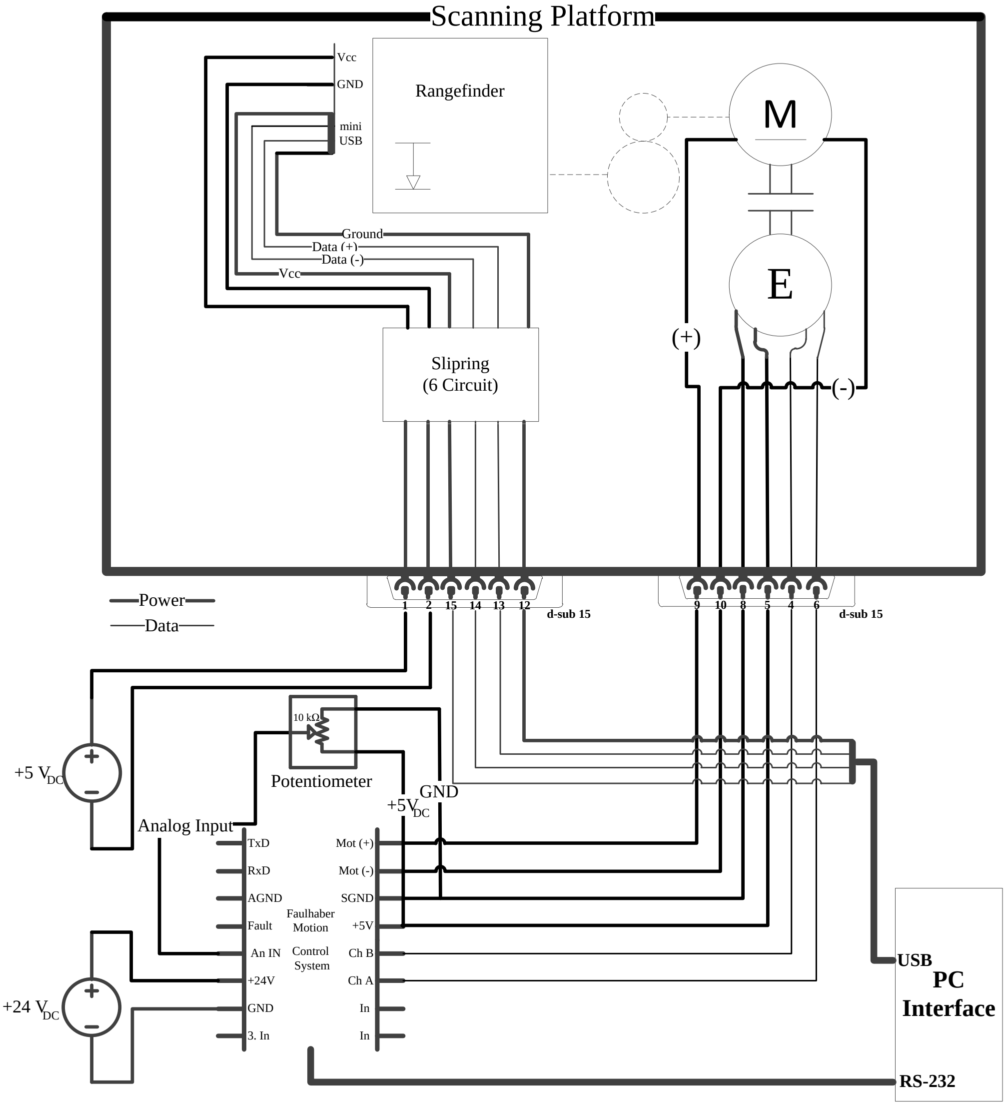

Figure B.1: Electrical Diagram of the Scanning Platform

APPENDIX C

COMPUTATIONAL AND COMMUNICATIONAL PLATFORMS USED FOR DATA HANDLING

All mechanical design and drawings have been done in CAD program. All the computational and communicational works related to data parsing of HOKUYO laser scanner and reading of position data of DC motor's encoder have been done in Linux environment. During the experiments, the data coming from laser scanner and encoder have been logged. Then Matlab has been utilized in order to process the data logged. By this way, some basic plots could have been created. A 3D cloud data viewing program whose name is Cloud Compare has also been used so as to create a detailed and clear view. The list of computer programs, used in this thesis, has been given below:

- CAD Program: Autodesk Inventor Professional 2011 (Student Version),
- 3D Cloud Data Plotting Program: Cloud Compare V2,
- Software Program: MATLAB 2010b, Linux UBUNTU.

ROS (Robot Operating System) provides libraries and tools to help software developers create robot applications. It provides hardware abstraction, device drivers, libraries, visualizers, message-passing, package management, and more. The steps of the data managing can be summarized as given in the following form:

Step 1: In order to activate ROS environment, call “roscore”.

Step 2: Call the laser scanner node that gets the data coming from Hokuyo and do parsing. The calling function is “rosrun hokuyo_node hokuyo”

Step 3: In order to get the position data coming from the encoder, use serial port communication environment of Linux. Faulhaber motion controller that is connected to the encoder of the DC motor is able to give position data in case a special string called “POS” is called. Send this string over the serial port and then listen the position data.

Step 4: Log the data coming from laser scanner and encoder in a text file.

Step 5: 3D Cloud Data Plotting Program can be worked only with introducing a specially created matrix. This matrix is constructed in Matlab environment by using the data logged in Step 4.

APPENDIX D

MATLAB CODE FOR TRANSLATION FORMULA

MATLAB code of translation formula has been given below:

```
load encoderDataLog.txt;
load laserScanDataLog.txt;
encoder = encoderDataLog - encoderDataLog(1);
laser = laserScanDataLog;
laserAngle = linspace(1,240,683);
N = 100;
rotationAngle = 0;
for i = 1:1:N
for j = 1:1:683
rotationAngle(i) = 360 * encoder(i) / 190e3;
X(i,j) = cosd(rotationAngle(i)) * cosd(laserAngle(j)) * laser(i,j);
Y(i,j) = sind(rotationAngle(i)) * cosd(laserAngle(j)) * laser(i,j);
Z(i,j) = sind(laserAngle(j)) * laser(i,j);
end
end
n = size(X);
Xnew = zeros(n(1)*n(2), 1);
Ynew = zeros(n(1)*n(2), 1);
Znew = zeros(n(1)*n(2), 1);
k = 1;
for i = 1:1:N
for j = 1:1:511
Xnew(k) = X(i,j);
Ynew(k) = Y(i,j);
Znew(k) = Z(i,j);
k = k + 1;
end
end
matrixA = [Xnew Ynew Znew];
delete matrixA.txt; disp('matrixA.txt is deleted');
save matrixA.txt matrixA -ASCII; disp('matrixA is saved');
```