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RUHR-UNIVERSITÄT BOCHUM

MechEng
Mechanical Engineering



Vietnamese-German University

DESIGN AND FABRICATE VIDEO RECORDING MECHANISM WITH SERVO-CONTROLLED-AUTO-FOCUS FOR 6-AXIS ROBOT GOFA FROM ABB

BACHELOR THESIS

VIETNAM 2022



Vietnamese-German University

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Design and fabricate video recording mechanism with servo-controlled-auto-focus for 6-axis robot GOFA from ABB

A Thesis Presented

By

Nguyen Vu Khanh Nhat



Submitted to the department of Mechanical Engineering of the
Vietnamese-German University
RUHR-UNIVERSITÄT BOCHUM and VIETNAMESE-GERMAN UNIVERSITY

in partial fulfillment

Of the requirement for the degree of

BACHELOR IN MECHANICAL ENGINEERING

Sep 2022

Major: Mechanical Engineering

Affirmation in lieu of oath

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I hereby declare in lieu of oath that I have produced the aforementioned thesis independently and without using any other means except the aids listed. Any thoughts directly or indirectly taken from somebody else's sources are made discernible as such.

To date, the thesis has not been submitted to any other board of examiners in the same or a similar format and has not been published yet.

HCMC, 29/11/2022



Nguyen Vu Khanh Nhat

Abstract

Many businesses are searching for original and creative ways to construct videos and clips incorporating complex camera motions or viewpoints as the filming industry continues to grow. On the other hand, a brand-new area of computer vision has emerged over the past few decades and is mostly focused on creating 3D models from collections of 2D photographs. The primary goal of this work is to build a robot-arm camera mount that can be used with the majority of commercially available digital cameras as well as a focus system that can adjust the cameras' focal length using the robot controller's program, allowing for single-program control.

The project's design process begins by using IDE tools to meticulously sketch out all the requirements and criteria for the system as a whole and each of its individual components. Afterward, conduct study and use advocacy tools to comprehend all the features and workings of the system. Following that, all planning, decision-making, and realization will be done in accordance with these limitations and the system's understanding. The use of tools to manage each stage of the process is also determined by their efficacy and suitability for the project; for example, requirements are summarized using an IDE's requirement lists, tasks and project planning are done using Gantt charts while 3D design and FEM analysis are done using Solidworks. The ABB program and simulation software will be used to drive the robot, and Arduino control the microcontroller module. Finally, the system is then examined for aspects of repeatability and stability.

The final result shows that hardware performance is adequate, the focus system can be adjusted to numerous focal ring locations of various lenses and effectively secure the gears so that they mesh snugly without slipping. In addition, the design of the camera housing demonstrates that it can securely fix most commercially available digital cameras to the robot. However, further tests will be required to increase software performance. For the project to be ready for field tests, more features like streamlined control and parallel operation between the robot's movement and focus system could be included.

The project will serve as the first concrete step toward integrating robotics into the fields of cinematography and computer vision, which were previously uncommon, particularly in Vietnam. Since robots will be the primary source of labor in the future, it will also inspire more students, researchers, and video enthusiasts to learn more about them.

Acknowledgement

I would like to thank Dr. Tran Trung Thanh, who is the project's supervisor, for his thorough advice on the necessary tools and methods. His project advice, counsel and support have been really helpful to me throughout the working process. Also, many thanks to Ms. Tuu Nguyen Thi for her support of the paper works.

I sincerely thank ABB Robotics in Vietnam for allowing me to borrow the robot for testing.

Last but not least I would like to give all the credit to my family and my girlfriend, who have been my greatest strength and motivation to finish this thesis

Nguyen Vu Khanh Nhat



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Chapter 1 Introduction

1.1 Background

As the filming industry continues to develop, many companies are looking for creative and innovative ways to compose videos and clips which integrate sophisticated camera angles or motions. These angles and motions, especially in the product shooting industry, usually require flexibility to capture shots or move between difficult angles with an accurately defined speed. To add up, some cameras used for live events or live sports filming are usually huge in size and weight, so human can hardly control these devices by themselves but instead resorts to other supporting, stabilizing systems. However, long-term operating experiences are indispensable when it comes to controlling these systems, but even with them, the filming product's repeatability and precision remain an everlasting problem.

On the other hand, a new field of computer vision has been developed for the past decades, mainly focusing on reconstructing 3D models using sets of 2D images. Manually capturing images is impossible for repeatability or high-precision camera locations/angles. Whereas having many cameras and fixing them in one place to take all images at once is cost-inefficient.

This paper introduces a camera mounting system for ABB's collaborative robot GOFA to tackle these problems. Robotic arms are well-known for their accuracy and repeatability; not only that, it can also handle high loads. These characteristics are suitable for mounting cameras or mobile phones onto the robot to create better filming production. The primary topic of this work is the creation of a camera mount that can be used with the majority of commercially available digital cameras and a focus system that can manage the cameras' focal length through the robot controller's program so that it can also be controlled in just one program.

1.2 Project description

1.2.1 Introduction

The following section will give a deep description of this project. The goal of project description is to give an overall picture of the project's scope and an overview of the standards and expectations set for the project. This section will first go through what motivated the

creation of this project. Then, with motivation in mind, the next part will discuss what specifically does this project will do, how it is a necessary addition to the world and what are the constraints and requirements that are needed to guide the project.

After a clear understanding of all of the above, a strategic plan will be shown through Gantt chart to answer the question “How are we going to make it happen?”. Next, since this project is self-funded, therefore high considerations of what components are going to be purchased; the Budget estimation table is introduced. Finally, the last part of Project description will give clear overall picture of how each function is necessary to build up a complete project.

1.2.2 Motivation

As small companies and enterprises multiply, they are in urgent need of improving the caliber of their advertising through brief videos. In order to make a good product video without having to spend a lot of money renting equipment or hiring a professional cameraman, product filmmaking is sometimes thought to be challenging to execute. This is due to the fact that some shots can't be conducted using cutting-edge stabilization equipment that can achieve a high repetition rate, or because some equipment can't be used to perform shots at odd angles in addition to stable motions and predetermined speeds. University

A recent development in computer vision focuses on creating 3D models from several 2D photos. But it is impossible to accomplish this without these two methods: the first is to set up numerous cameras and strategically arrange them all around the model, but this is expensive and requires different camera setups for each model because each one varies in size. The second method is to use a robot system to hold the camera and move it in a very repeatable and precise manner.

1.2.3 Objectives

The goal of the project is to create a camera mounting system that will allow any common digital camera to be attached to the robot arm as well as a focus system that will allow the camera's focal length to be adjusted using the same software that plans and directs the robot's movements. So that different types of cameras and other camera equipment can be mounted to the robot, the camera mounting system is made to be sturdy and lightweight. A servo motor that is controlled by analog signals coming from the robot controller will be included into the

focus system. A micro-controller is used to convert analog signals to PWM signals. Finally, a built-in feature that enables users to move the robot body to any location they choose and save that position before the saved locations can subsequently be used by the robot to manage and build robot routes.

1.2.4 Impact

The robot-camera project can give many businesses in Viet Nam more access to this robot technology by reducing the cost of buying or renting these outside Viet Nam, they can, in result, create better commercial videos or media products for their social media. For example, they can create moving time-lapse videos (which before can only be done by moving the camera centimeter by centimeter after each frame is taken), or making dynamic tilting angle for their products shooting. They can also fast-tracing an object moving around with the robot arm or design a fixed robot paths and record many objects/backgrounds with the same paths that later they can layer them together in the editing phase.

The project also grants opportunities for researchers or students that major in computer vision to study/research their projects like mapping, 3D constructing, or creating a tracing algorithm which the camera will always trace the object wherever it goes.

1.2.5 Constraints

Constraints are necessary for the production of this project, as they will create realistic boundaries and set a basic framework to work with. This part will examine all the constraints and how they affect product's overall design. There are four main factors after thorough consideration: time, money, sustainability, and safety. This section will mainly discuss the overall concept behind these factors while the 1.2.6 section will go into detail.

Time will be the most essential factor for this project because the official duration for doing a thesis will be 3 months, excluding 1 month of extension. During the project, there will be dead-time where purchased components will need some shipping time and manufacturing parts will also spend some time for the manufacturing company. With this in mind, during this time, other tasks that do not evolve physical components will be done in parallel. Also, there should be back-up time in case the manufacturing company does not meet the expectations and

threshold (which is customarily occurred in Viet Nam, especially small, private manufacturing companies that are comparably cheap in the market)

Because this project is self-funded, which means the author of this paper is financing it. Therefore, with a limited budget, good planning of how the money is spent and changing mindset when it comes to economic decisions are necessary. To be more precise, before making any decisions to buy or produce a product, it is crucial to conduct meticulous calculations to determine a good threshold. From that point on, all financial decisions will revolve around selecting the most affordable option that satisfies the requirements. In fact, this is actually a smart technique that helps to keep the product as affordable as possible for the customers while also forming a positive buying habit. Overbuying could have a negative impact on the project, such as making it too costly or heavy. In this situation, both elements should be removed from the project because if the mounting is too heavy, the system will wobble a lot or the robot won't be able to move it. The system may also drive away many target clients, such as students, researchers, or small enterprises, if it is too costly.

Increasing a device's lifespan before it is taken out of service and discarded is the aim of sustainable design. By extending the time that the gadget may be maintained, this is accomplished. There are numerous approaches to guarantee that the equipment is simple to maintain. The device's components should all be separately interchangeable. Using a modular design, which emphasizes having all pieces be detachable without removing other components as well, accomplishes this. This means that each component needs to be as independent as feasible. These sustainability limitations have been carefully considered in the design of this product. This device's parts will all be exchangeable. This is accomplished by designating a certain location within the housing where it can anchor and be removed from. The complete product can be disassembled so that all parts are accessible. Because each component serves a single, distinct purpose, this is achievable.

There are many things that need to be considered when working with a robot. Firstly, the robot can potentially collide with the user if the user is not careful enough and walks into the robot's working area. Conversely, the robot could collide with other nearby objects if the user's program is not correct. Impacts made by robot arms are usually hazardous and could harm the robot and the object/user altogether. To combat this, the robot chosen needs to have safety features such as immediate stop when the sensors inside the robot can sense a collision.

Alternatively, it can have an outer external sensor where if it detects any human in the working area of the robot, the robot will slow down or stop completely until the human removes himself out of the area. The mounting system will also chamfer all the sharp edges to minimize damages inflicted on the subject if there was an impact.

1.2.6 Requirements list

Requirements list contains all the specifications that are extracted from the Constraints section, but the content is "translated" to "engineering language" so that the engineer can start developing their work based on the already discussed constraints (Vajna, 2020, p. 37).

Moreover, the requirements are categorized into eight categories: geometry, kinematic, forces, energy, material, safety, operation, and maintenance. These requirements are the fundamentals for all engineering design products, meaning every product must have at least 8 of these groups in the list. In addition, to not hold down the imagination, each requirement can be divided into either Demand (D) or Wish (W). "Demands" are the requirements that must be satisfied, while "Wishes" can be seen as optional.

In geometry section, the height, width, and length are estimated based on the dimension of the camera; this is intentional as it suggests that the entire system should be kept compact. Parts responsible for connecting the mounting system, the camera, and the robot should strictly follow the devices' standards.

In kinematic, the system is required steadiness. As well as all the other moving components on the system, i.e., the lens and motors should have enough spacing, and they do not collide with other parts of the system when in motion. In addition, the camera mounting system is considered to hanging on the robot's flange, meaning that the robot's flange will parallel to the ground while the lens is pointing horizontally. This setup is believed to be more stable because it will reduce the lever length, thusly reducing the torque acting on the robot and the mounting system.

The main acting force is the camera's gravity, which is 0.55kg in weight (Nikon, 2012), so this force will be considered when designing the frame. To keep the frame as light as possible, the material to be used should be stainless steel or PA plastic, with a coating of black color. The

color black is often used for videography equipment because it does not reflect any light, so it will not interfere with the scene's lighting (Mitchell, 2020).

In safety section, two demands are no sharp edges and internal force sensor. While all of the robots with a reach of less than 1m usually have force sensors installed inside the robot, the collaborative robots have a more sensitive sensor to ensure no impact can hurt the user. In ABB, SafeMove sensors can detect humans moving toward the robot's working area and immediately interrupt the robot's action by either slowing it down or stopping it. However, this is considered a Wish because internal force sensor is just enough for the job, while having these sensors requires more research time and budget.

An ABB IO device should be used with the ABB robot so that Robotstudio can operate both devices. Robotstudio is a software from ABB that controls, simulates, and installs systems... for the robot and any IO devices. Further detail of Robotstudio will be in this paper, but for now, it should be known that using an IO device and robot from ABB, the entire system can be controlled through one software.



Last but not least, to attain high sustainability or maintenance, the system will use no adhesive but bolts and nuts to connect everything; this will ensure that all parts can easily be replaced.

Table 1: Requirement list

Date of change	Demand (D) or Wish (W)	Requirements	Responsibility
12/9/2022	D	<u>Geometry</u> Height= 170mm	Nguyen Vu Khanh Nhat
12/9/2022	D	Width= 130mm	
12/9/2022	D	Length= 150mm	
12/9/2022	D	Fit to the robot arm's tool flange	
12/9/2022	D	Fit the camera's screw hole (ease of attachability)	
12/9/2022	D	<u>Kinematic</u> Moving around steadily (for both linear and rotation movement)	
12/9/2022	D	Make room the for focal ring attachment	
12/9/2022	D	Locating the tool so that it won't collide with the robot's body	
7/10/2022	D	<u>Forces</u> Maximum weight <= 5kg	
12/9/2022	D	<u>Energy</u> Gear transmission	
12/9/2022	D	Analog control the servo	
12/9/2022	D	2 18651 batteries	
12/9/2022	D	<u>Material</u> Light + thin: stainless steel, PA plastic	
12/9/2022	W	Black color	
12/9/2022	D	<u>Safety</u> No sharp edges	
	D	Internal force sensor	
	W	External human sensor	
12/9/2022	D	<u>Operation</u> By ABB IO device + robot Program by Robotstudio	
12/9/2022	W	<u>Maintenance</u> No lubricant needed	
	D	Use bolt and nut (no adhesive)	

1.2.7 Gantt chart

Gantt chart is used to plan out all the essential tasks that need to be performed in a timely order. The project is split into 3 phases: research and design, development, and testing. While completing these tasks, it should be prioritized that they must serve the requirement lists, and any changes to the Gantt chart must also stay in line with what was defined in the list of requirements.

The first month outlines all the project conditions and restrictions and generates all the necessary functions to comprehend the big picture. During this time of the first month, four weeks have been used to have the first concept drawing and turn it into 3D. To be able to draw, all of the required components have to be listed out first and drawn in the 3D software. Finally, in the last week of September, all the components are ordered, and the manufacturing company is contacted to start discussing the next phase.

For all of October to the middle of November, the project was mainly in the developing phase, testing which components should be used or which structure is better for the application. This phase takes the most time due to waiting for the manufacturing company's work time and the shipping time of the products. In order to fill this gap, research and programming for the microcontroller and the robot are performed simultaneously. Therefore, writing reports is in constant update, acting like a log for writing down all the options' aspects and comparing all the options to pick out the most suitable one finally.

Finally, the last two weeks will be utilized to test the whole system, from software to hardware, through repeatability and stability tests.

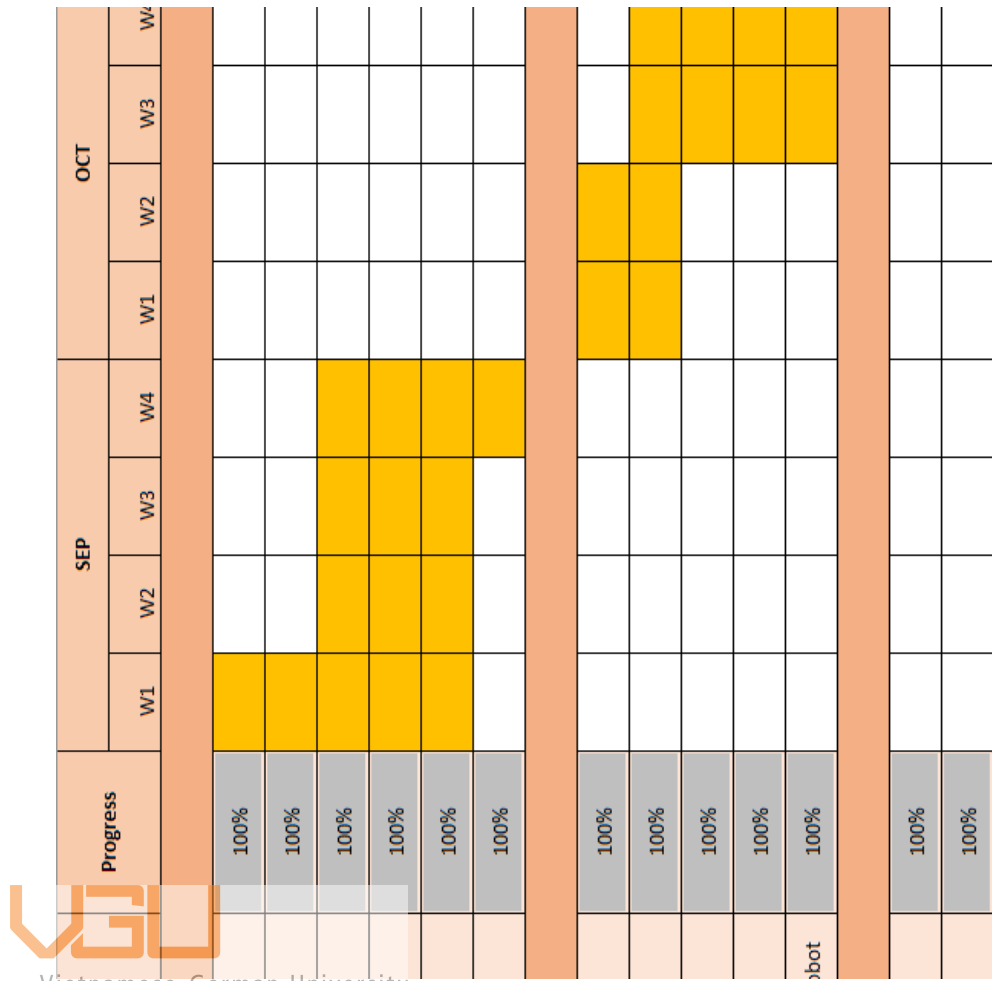


Figure 1: Gantt chart

1.2.8 Budget list

An organized table with all the purchase and manufacturing prices may be found below. As can be seen from the data, the cost of manufacturing and printing is greatest at 6 million VND. This price includes two times for producing and printing the metal, as well as several times for returning the finished product to the manufacturer to correct minor mistakes. These mistakes include twisted and distorted pieces as well as missing threads. The cost of the microcontroller and other electronics parts, such as two motors, two batteries, a battery case, a battery charger, and a power source cord, comes in second place. Last but not least, there are little elements that barely register in the final cost, such as bolts and nuts, cables and wires, and potentiometers...

A total of about 7 million VND has been spent on this project. Note that since the author already has a DSLR camera and lens, these expenses do not include that.

ITEM/SERVICE	LOCATION	NOTE	UNITS	VND / UNIT	TOTAL COST
SERVO SG90	Hshop - Thu Duc - HCMC	N/A	1	VND 34,000.00	VND 34,000.00
M-F wire	Hshop - Thu Duc - HCMC	N/A	1	VND 28,000.00	VND 28,000.00
POTENTION METER 10K	Shopee	N/A	1	VND 12,000.00	VND 12,000.00
ARDUINO UNO ADHESIVE CHIP	Hshop - Thu Duc - HCMC	N/A	1	VND 185,000.00	VND 185,000.00
POWER Adapter	Hshop - Thu Duc - HCMC	N/A	1	VND 55.00	VND 55.00
MM wire	Hshop - Thu Duc - HCMC	N/A	1	VND 28,000.00	VND 28,000.00
Manufacturing + 3D printing	MEC 3D - Thu Duc - HCMC	N/A	2	VND 3,000,000.00	VND 6,000,000.00
CONNECTOR	Dan Sinh market - Dis 1 - HCMC	N/A	2	VND 5,000.00	VND 10,000.00
ZIP TIE	Dan Sinh market - Dis 1 - HCMC	N/A	1	VND 10,000.00	VND 10,000.00
SERVO LewanSoul LD - 27MG	Hshop - Thu Duc - HCMC	N/A	1	VND 425,000.00	VND 425,000.00
Bolt and nuts	Dan Sinh market - Dis 1 - HCMC	N/A	1	VND 60,000.00	VND 60,000.00
18650 battery	Hshop - Thu Duc - HCMC	N/A	2	VND 30,000.00	VND 60,000.00
18650 charger	Hshop - Thu Duc - HCMC	N/A	1	VND 180,000.00	VND 180,000.00
Battery case	Hshop - Thu Duc - HCMC	N/A	1	VND 7,000.00	VND 7,000.00



TOTAL COST
VND 7,039,055.00

Figure 2: Budget estimation

1.2.9 Function structure

A function structure diagram is used to manage and comprehend all of the functional characteristics of the entire system. Vajna stated in a general procedure of design, a full description of the technical system should be considered after the requirements are listed (2020, p. 8)

Every block with a dashed border is referred to as a system or a sub-system and symbolizes an entire section of the project that is in charge of a specific task.

The power supply is represented by a red line, which denotes that the robot, servo, controller, and IO device should all receive power.

The camera system will receive analog signals from the IO device (represent as a yellow line) and motion data from the robot (shown as a green line). From these, the controller will deal with and transmit the signal to the servo from analog to PWM. The gear will subsequently be moved by the servo, which will cause the camera's lens to move. The entire robot camera will output videos and input path programming and IO programming.

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By understanding this diagram, the overall function of the system is grasped and how each component of the system works with one another. For instance, the ABB robot requires power source as well as path programming from Robotstudio, then it can produce motions for the system, which the motions are the input for the camera system. Another example is the input of the IO device is an external power source and an IO program. The output of the IO device is analog signal, which goes directly to the camera system, to be more specific the micro-controller. The micro-controller then controls the Servo through PWM signal and so on...

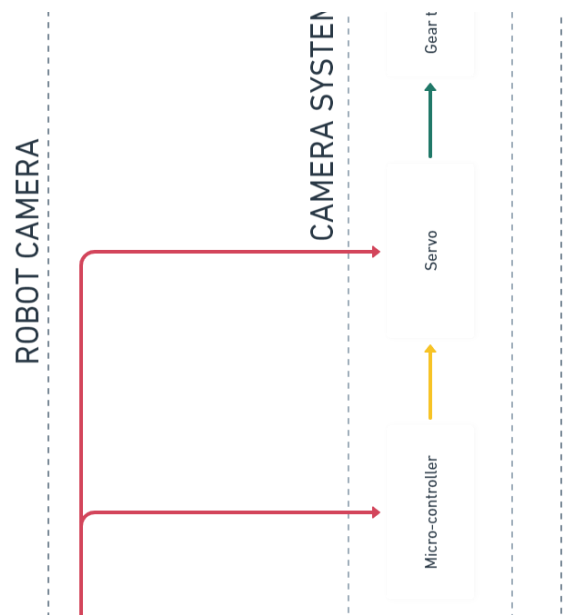


Figure 3: Function structure

Chapter 2 Related work

2.1 State of the art handheld stabilization devices

There are supporting gadgets available on the market today that enable users to hold and move the camera with smoother motion while minimizing any jitter movements generated by the user's body. Many camera-technology companies, including DJI, have developed handheld gimbals that can enhance the smoothness of videos from attached devices like cameras or cellphones (DJI™, 2015). There are typically two different kinds of gimbals; one counterbalances with motors like Osmo from DJI, and the other does it with a counterweight or other supporting structure that holds the camera like Steadimate-S from Steadicam (The Tiffen Company, 2019). Even though these gadgets are commonly used, human variables are still taken into consideration, making it challenging to film videos consistently. The range of rotation on their axes and the moment of inertia of the counter-weight make it challenging to create shots that demand for swift camera movements or access to a variety of angles. Robot cameras can overcome all of these drawbacks since repeatability, stability, adaptability, and high-speed movements are standard elements of a robot arm. ABB's software can drive a robot arm mounted with a camera set on a running track as an external axis, allowing a robot with an arm reach of up to 1m (ABB, 2021) to move around while taking pictures.



Figure 4: DJI Osmo gimbal (DJI™, 2015)



Figure 5: Steadicam (The Tiffen Company , 2019)

2.2 Robotics application in videography/photography

Short Video Advertisement is a group of students' project that focuses on creating an algorithm that suggests to users every camera position, angle, and movement needed to produce a

fantastic commercial video (Gavrilova et al., 2019). This initiative aids novices who are having trouble putting together an advertisement without having to learn and get filming experience. The algorithm will study and decide how each shot should be taken using AI. The shots are planned and generated on their application after the product kind and visual style have been decided upon, with the inclusion of the robot's routes and velocity which are likewise calculated in their framework and utilized to the robot. However, the research only uses a smartphone as a recording device, with the phone being held in place by the robot's gripper. This excludes people who use other video-shooting tools, such as a DSLR camera or a mirrorless camera. Which misses a significant portion of users who operate micro- and small-scale companies and who typically use digital cameras rather than smartphones. This article fills that gap and enables the use of short video advertisements in the market for popular digital cameras.

2.3 Video capturing robot

Motorized precision can be considered a direct competition because it is one of first companies to share this idea and bring it to the world. They have robot cameras with different sizes for sale or rent. Their products consist of 4 types of robotic arms (4 different sizes) with a mounting system for cameras and an application for easy programming of the robot's path. However, one of the main differences between Motorized Precision and this project is the target customer. While Motorized Precision are looking for big companies, this project mainly aims at small businesses and students. This leads to the difference of price range between the two. According to No Film school, one day rent of MP costs about \$4000, (No Film School, 2016) this is usually unaffordable for many small brands and students, which are the target customers of this project. With rental service and low manufacturing cost, GOFA's robot camera can be more cost efficient.

Chapter 3 Detailed design

3.1 Robotic arms

3.1.1 Industrial robot IRB 1200

ABB's industrial robot IRB 1200 is a 6-axis, compact, flexible, high-speed robot. The robot has a small design of roughly 1m in height and compact housing. This robot has two options, one with a handling capacity of 5kg and the reach going up to 0.9m, hence the name IRB 1200-5/09. While the other option is IRB 1200-7/07, with the second having a more significant load but having to sacrifice reach in compensation. The camera system is not heavier than 5kg, so that both options can be considered. However, the option with more extended reach is more likely to be chosen because the robot camera favors maximum space coverage.

It is given the title flexible because this robot can be mounted at any angle; this includes upside-down mounting. Ceiling-mounting camera robots can often be seen in indoor concerts (not to take up much space of the audience) or sports stadiums. Therefore, this characteristic should be considered as well. Each axis has its own working range and motion speed, but the highest speed can reach 600 degrees per second while maintaining 0.025mm in repeatability.

This robot can be controlled by the IRC5 controller or OmniCore controllers; the comparison between the two will be discussed further. Nevertheless, the OmniCore is a new generation controller with an option for block-drag-and-drop programming, while the IRC5 programming software looks similar to C++ programming.

The robot comes with IP40 protection as standard, but there are also available options for purchase, i.e., Food Grade Lubrication which can ensure hygiene for food and beverage applications. For this project, IP40 protection, which is protection against objects from 1mm in size, is usable since our customers' behavior suggests working in research labs or un Hazardous environments like studios, schools, universities, or public indoor sites...

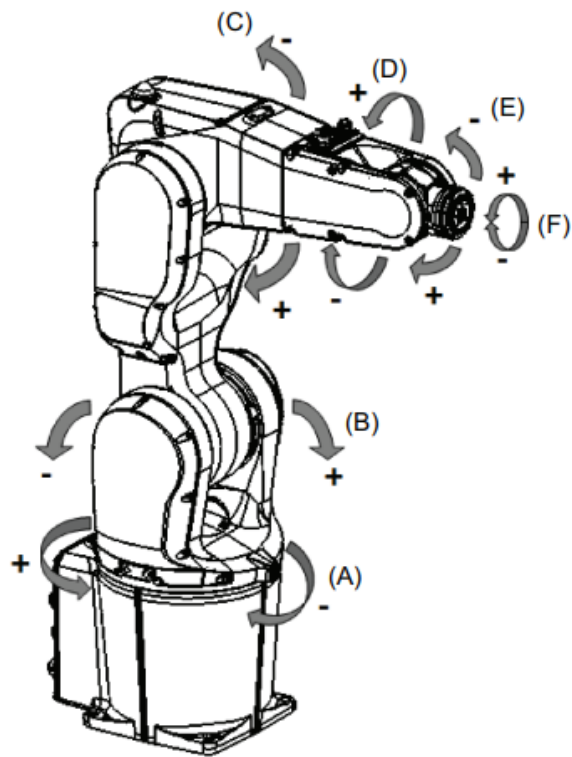
Below is a summary table of all the specifications of IRB1200. For the sake of this paper, the IRB1200-5/09 is used for reference because it is the available option in the ABB workshop

Viet Nam. The following data discussed in this subsection can be found in the IRB1200's product specification (ABB, 2019).

Table 2: IRB1200 5/0.9 specification (ABB, 2019)

Handling capacity	5kg	Basic information
Reach	0.9 m	
Weight	54 kg	
Power consumption	0.45 kW	
Controller	Omnicores, IRC5	
Protection standard	IP40	
Axis 1	+170° to -170°	Working range
Axis 2	+130° to -100°	
Axis 3	+70° to -200°	
Axis 4	+270° to -270°	
Axis 5	+130° to -130°	
Axis 6	+400° to -400°	
Joint 1	288°/s	Joint speed
Joint 2	240°/s	
Joint 3	300°/s	
Joint 4	400°/s	
Joint 5	405°/s	
Joint 6	600°/s	

Structure and axis of IRB1200/5/0.9



xx1300000365

Position	Description	Position	Description
A	Axis 1	B	Axis 2
C	Axis 3	D	Axis 4
E	Axis 5	F	Axis 6

Figure 6: IRB1200-5/0.9 structure and axes (ABB, 2019, p.12)

Dimension of IRB1200-5/0.9:

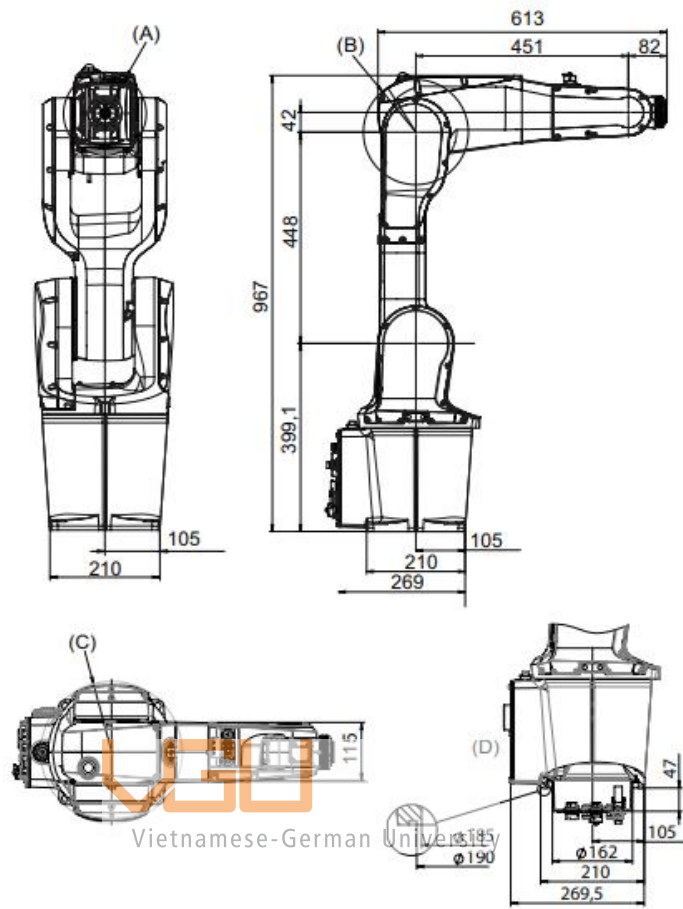
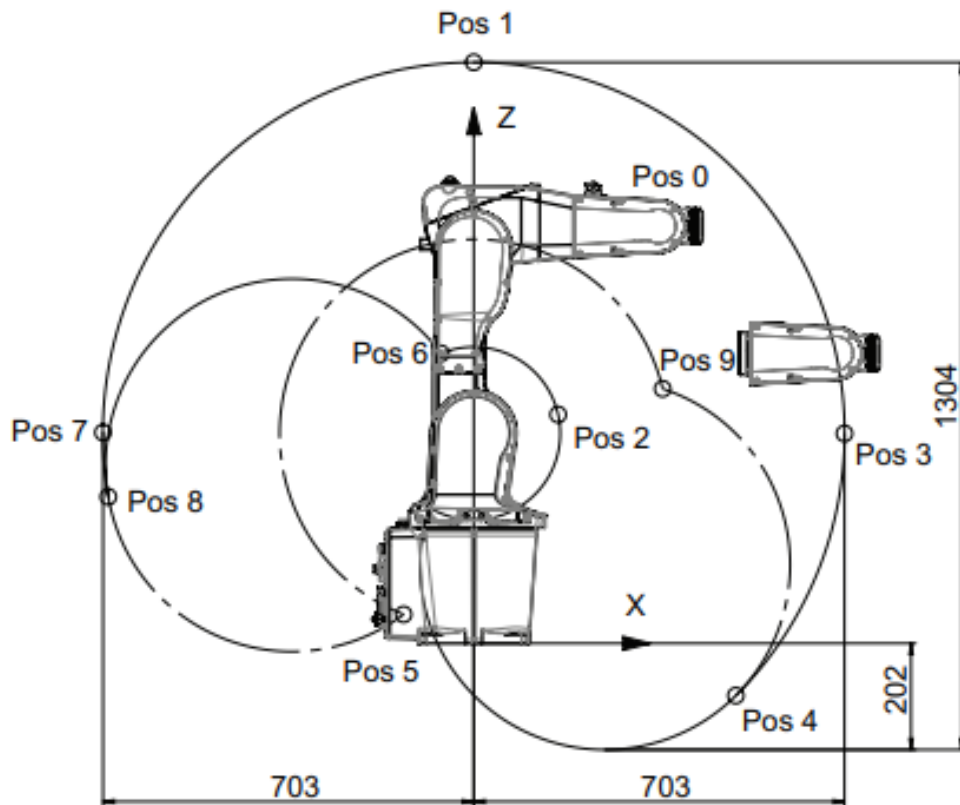


Figure 7: IRB1200-5/0.9 dimensions (ABB, 2019, p.16)

Working range of IRB 1200-5/0.9:



xx1300000386



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Position in the figure	Positions at wrist center (mm)		Angle (degrees)	
	X	Z	Axis 2	Axis 3
Pos0	351	791	0°	0°
Pos1	0	1102	0°	-83°
Pos2	160	434	0°	+70°
Pos3	703	398	+90°	-83°
Pos4	497	-99	+135°	-83°
Pos5	-133	55	-100°	-200°
Pos6	-62	550	-100°	+70°
Pos7	-703	400	-90°	-83°
Pos8	-693	278	-100°	-83°
Pos9	358	488	+135°	-200°

Figure 8: IRB1200 5/0.9 working range (ABB, 2019, p.46)

3.1.2 Industrial robot IRB 1300

The next robot option for this project is IRB. This industrial robot has four types, which categorized by their load handling capacity and their reach, see table below for more details, but a brief look can tell this version has much more capacity and reach compared to IRB 1200 (ABB, *Product specification IRB1300* 2020):

Table 3: Comparison between IRB1300 versions (ABB, Product specification IRB1300 2020):

Type	Load capacity (kg)	Reach (m)
IRB 1300-11/09	11	0.9
IRB 1300-10/1.15	10	1.15
IRB 1300-7/1.4	7	1.4
IRB 1300-12/1.4	12	1.4

For reference of this paper, IRB 1300-11/09 is shown as a representative of this robot line due to the availability of this robot in the workshop in Viet Nam. With a payload of 11 kg, this can open more opportunities for the camera system to have bigger size cameras or more equipment attached, like lights, microphones, screens...



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Similarly, this robot can be floor and wall-mounted, for each mounting will require an in-depth calibration process before use because the load structure of the robot when mounting on the floor is different than on the wall. For the standard option, IRB1300 has an IP40 protection class, but there are available options for IP67 if it ever works in harsh and contaminated areas.

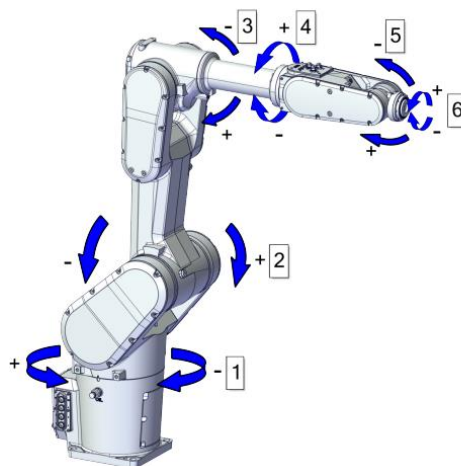
The robot can only be controlled by the new OmniCore controllers. As mentioned above, this controller allows users to program robots easily by simply dragging the function blocks and modifying parameters inside it; programming experience isn't required. This is ideal for this project's target customers who want to create a camera path for themselves, as well as beginners or students who want to learn about controlling robots through this application. This is a basic start to learning programming.

The following data discussed in this subsection can be found in the IRB1300's product specification. (ABB, *Product specification IRB1300* 2020)

Table 4: IRB1300-11/0.9 specifications (ABB, Product specification IRB1300 2020)

Handling capacity	11kg	Basic information
Reach	0.9 m	
Weight	75 kg	
Power consumption	494 W	
Controller	Omnicores	
Protection standard	IP40	
Axis 1	+180° to -180°	Working range
Axis 2	+130° to -100°	
Axis 3	+65° to -210°	
Axis 4	+230° to -230°	
Axis 5	+130° to -130°	
Axis 6	+400° to -400°	
Joint 1	243°/s	Joint speed
Joint 2	255°/s	
Joint 3	330°/s	
Joint 4	500°/s	
Joint 5	420°/s	
Joint 6	720°/s	

Structure and axes of IRB1300-11/0.9



Pos	Description	Pos	Description
1	Axis 1	2	Axis 2
3	Axis 3	4	Axis 4
5	Axis 5	6	Axis 6

Figure 9: IRB1300-11/0.9 structure and axes (ABB, Product specification IRB1300 2020, p.12)

Dimension of IRB1300-11/0.9

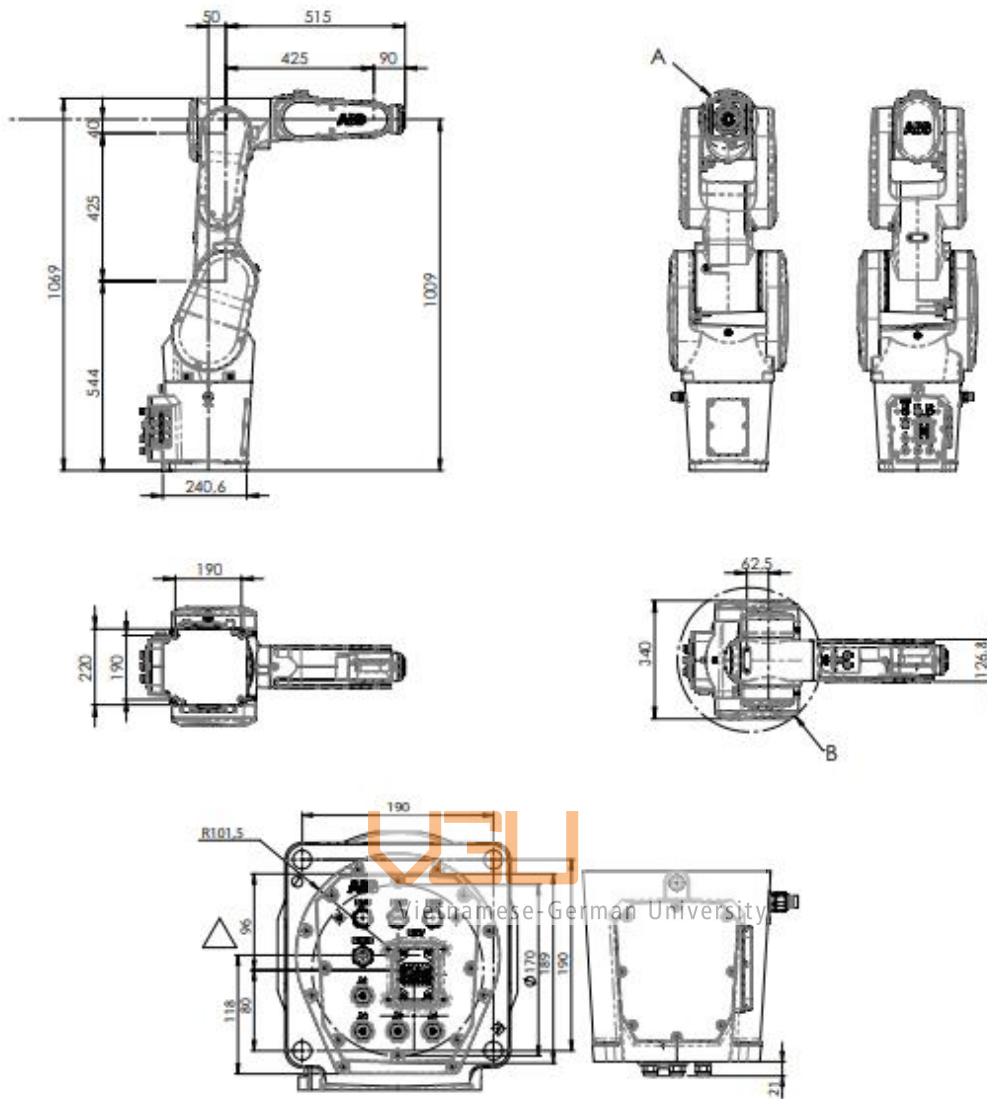
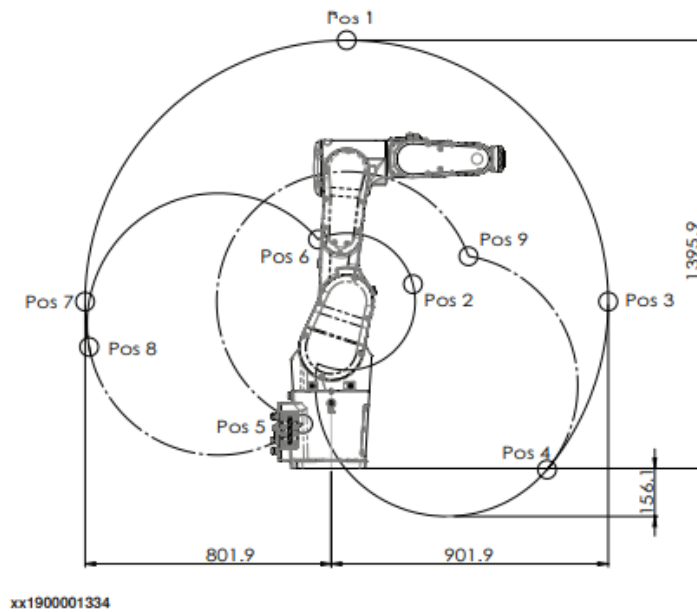


Figure 10: IRB1300-11/0.9 dimensions (ABB, Product specification IRB1300 2020, p.18)

Working range of IRB1300-11/0.9



Positions at wrist center and angle of axes 2 and 3

Position in the figure	Positions at wrist center (mm)		Angle (degrees)	
	X	Z	axis 2	axis 3
pos0	475	1009	0°	0°
pos1	50	1395.9	0°	-84.6°
pos2	265.9	600.7	0°	65°
pos3	901.9	544	90°	-84.6°
pos4	702.6	-3.6	130°	-84.6°
pos5	-64.7	170.3	-100°	-210°
pos6	-43.3	746.7	-100°	65°
pos7	-801.9	544	-90°	-84.6°
pos8	-788.9	396.1	-100°	-84.6°
pos9	410	696.3	130°	-210°

Figure 11: IRB1300-11/0.9 working range ((ABB, Product specification IRB1300 2020, p.21)

3.1.3 Collaborative robot CRB 15000

CRB 15000, or GOFA, is a collaborative 6-axis articulated robot. A collaborative robot, commonly referred to as a cobot, is a machine that can pick up tasks quickly and help people. Autonomous robots or industrial robots, on the other hand, are hard-coded to consistently perform a single task, operate independently, and remain immobile. Small, lower-power robots may now be aware of their surroundings and safely carry out a variety of tasks in close proximity to human employees because of advancements in mobile technology, machine vision, cognitive computing, and touch technology (including collision avoidance). When assisting a human, a cobot can swiftly pick up new skills through demonstration and reinforcement learning. This feature is known as "Lead-through" for GOFA, where a user can touch and drive the robot to a specified spot and instruct it to include it in a path. Then the robot can immediately perform all the taught points. GOFA also has force sensors in it so that when the robot detects motion from the user, the motors inside will be activated and move in the direction where the user applies force, thus reducing the effort to teach the robot.

Another feature that allows GOFA to work in proximity to humans is that its force sensor located in every joint can halt the robot in milliseconds if there is any collision (ABB, 2022). Also, with a weight of 28kg, there are applications where the robot is fixed on a cart and transported to many places down the production line and work there.

CRB 15000 holds the capacity of loading 5kg in terms of handling capacity and can have a maximum reach of 0.95m. This robot can be mounted on any vertical or horizontal surface. It has a protection class of IP54 which can protect itself from the most amount of dust and water splashed from all directions.

The following data discussed in this subsection can be found in the GOFA's product specification (ABB, 2021).

Table 5: CRB15000 specifications (ABB, 2021)

Handling capacity	5kg	Basic information
Reach	0.95 m	
Weight	28 kg	
Power consumption	202 W	
Controller	Omnicores	
Protection standard	IP54	
Axis 1	+180° to -180°	Working range
Axis 2	+180° to -180°	
Axis 3	+85° to -225°	
Axis 4	+180° to -180°	
Axis 5	+180° to -180°	
Axis 6	+270° to -270°	
Joint 1	125°/s	Joint speed
Joint 2	125°/s	
Joint 3	140°/s	
Joint 4	200°/s	
Joint 5	200°/s	
Joint 6	200°/s	

GOFA structure and axes

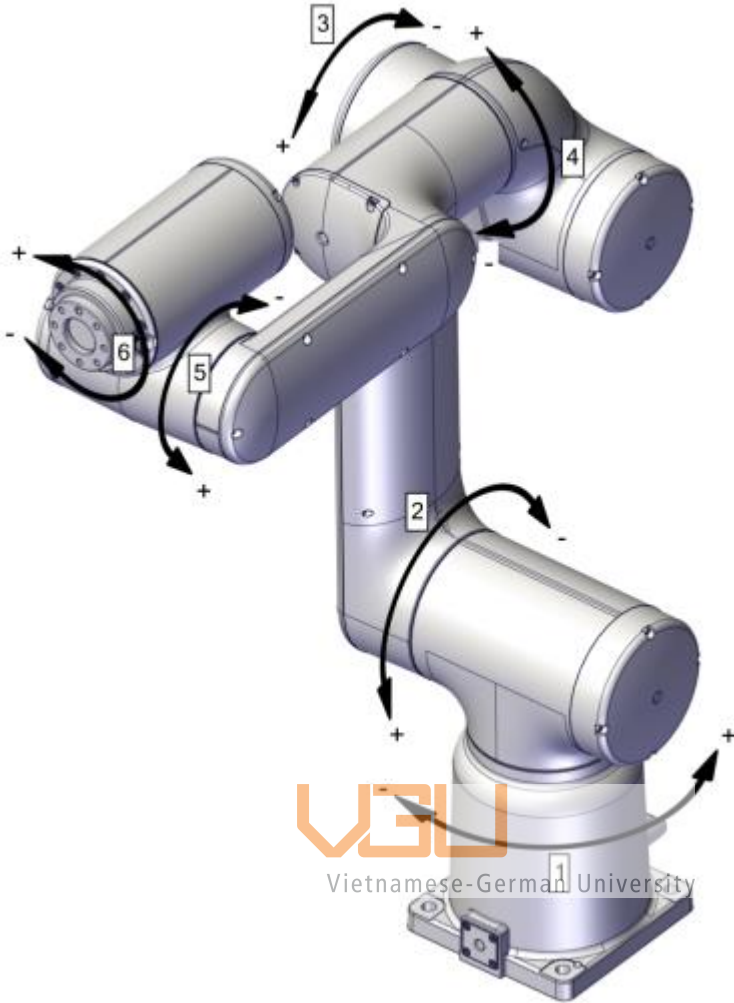
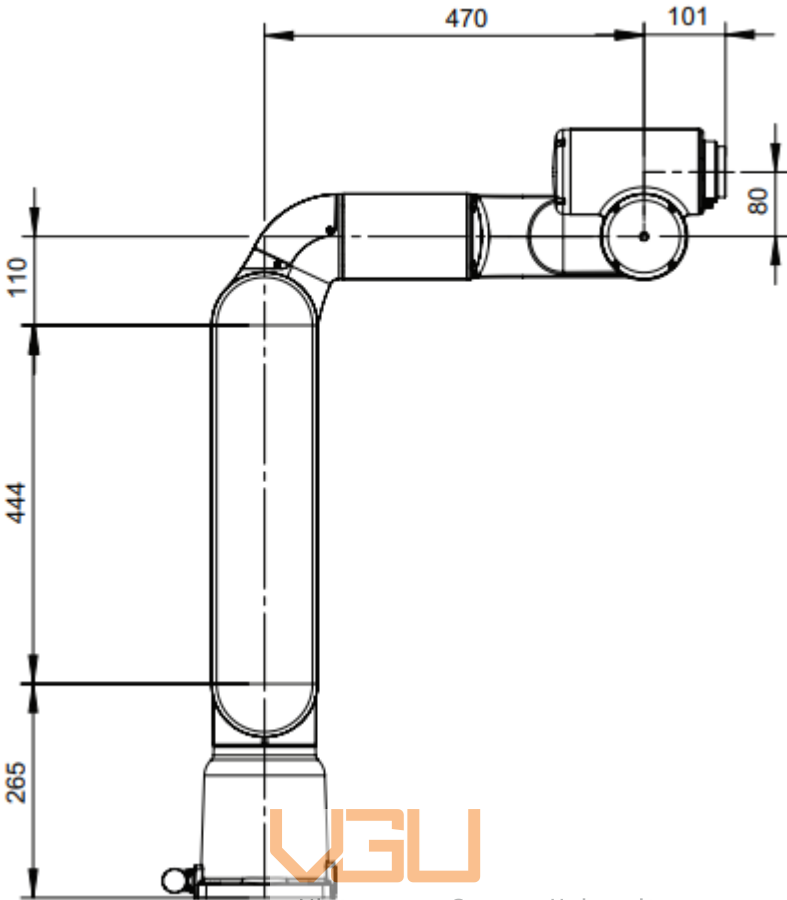


Figure 12: GOFA structure and axes (ABB, 2021, p.34)

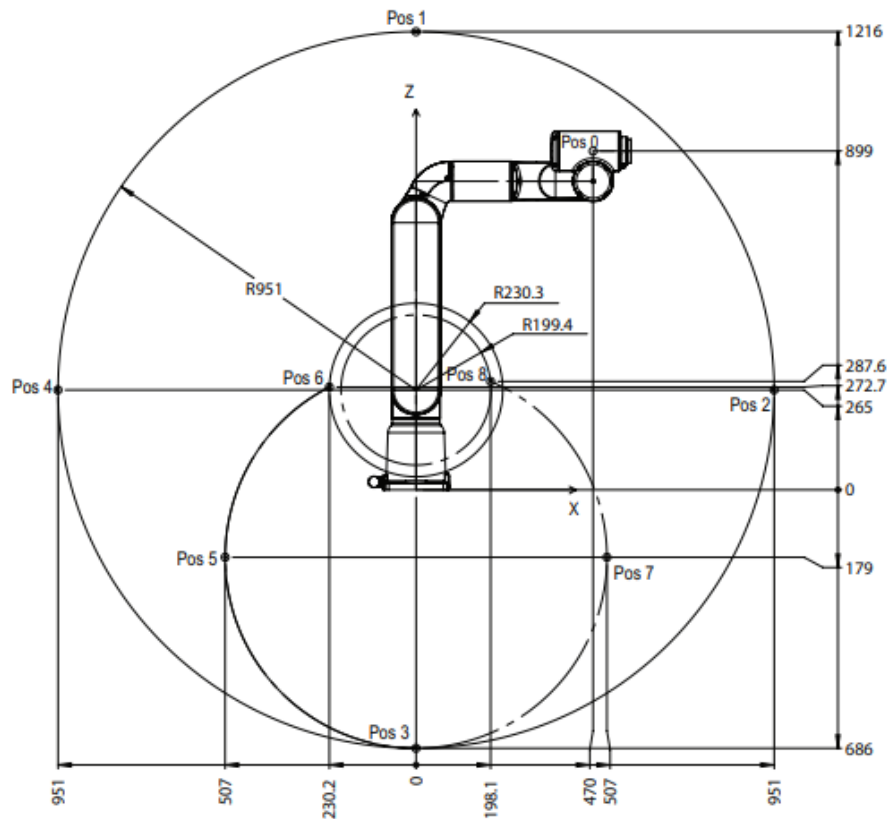
GOFA dimension



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Figure 13: GOFA dimension (ABB, 2021, p.23)

GOFA working range



xx2000002410

Positions at intersection point of axes 4-5-6 and angle of axes 2 and 3

Position in the figure	Positions at wrist center (mm)		Angle (degrees)	
	X	Z	axis 2	axis 3
pos0	470	899	0°	0°
pos1	0	1216	0°	-68°
pos2	951	265	90°	-68°
pos3	0	-686	180°	-68°
pos4	-951	265	-90°	-68°
pos5	-507	-179	180°	22°
pos6	-230.2	272.7	180°	85°
pos7	507	-179	180°	-158°

Figure 14: GOFA working range (ABB, 2021, p.42)

3.1.4 Final decision

Overall comparison of 3 robots:

Table 6: Comparison between robots

		IRB 1200	IRB 1300	CRB 15000
Basic Information	Handling capacity	5kg	11kg	5kg
	Reach	0.9 m	0.9 m	0.95 m
	Weight	54 kg	75 kg	28 kg
	Power consumption	0.45 kW	494 W	202 W
	Controller	Omnicores, IRC5	Omnicores	Omnicores
	Protection standard	IP40	IP40	IP54
Working range	Axis 1	+170° to -170°	+180° to -180°	+180° to -180°
	Axis 2	+130° to -100°	+130° to -100°	+180° to -180°
	Axis 3	+70° to -200°	+65° to -210°	+85° to -225°
	Axis 4	+270° to -270°	+230° to -230°	+180° to -180°
	Axis 5	+130° to -130°	+130° to -130°	+180° to -180°
	Axis 6	+400° to -400°	+400° to -400°	+270° to -270°
Joint speed	Joint 1	288°/s	243°/s	125°/s
	Joint 2	240°/s	255°/s	125°/s
	Joint 3	300°/s	330°/s	140°/s
	Joint 4	400°/s	500°/s	200°/s
	Joint 5	405°/s	420°/s	200°/s
	Joint 6	600°/s	720°/s	200°/s

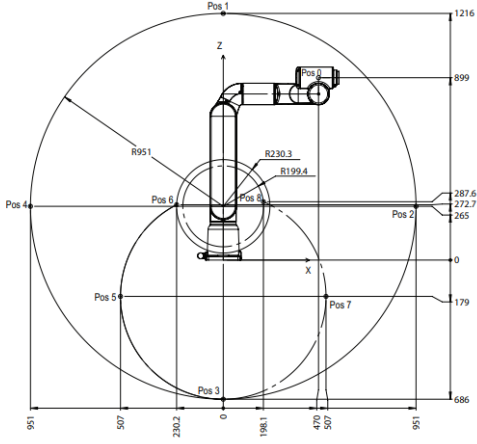
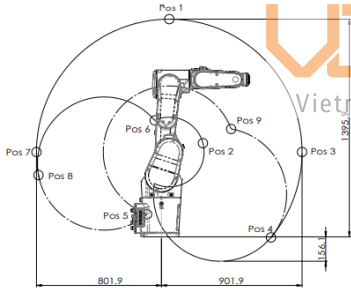
Dimension comparison:

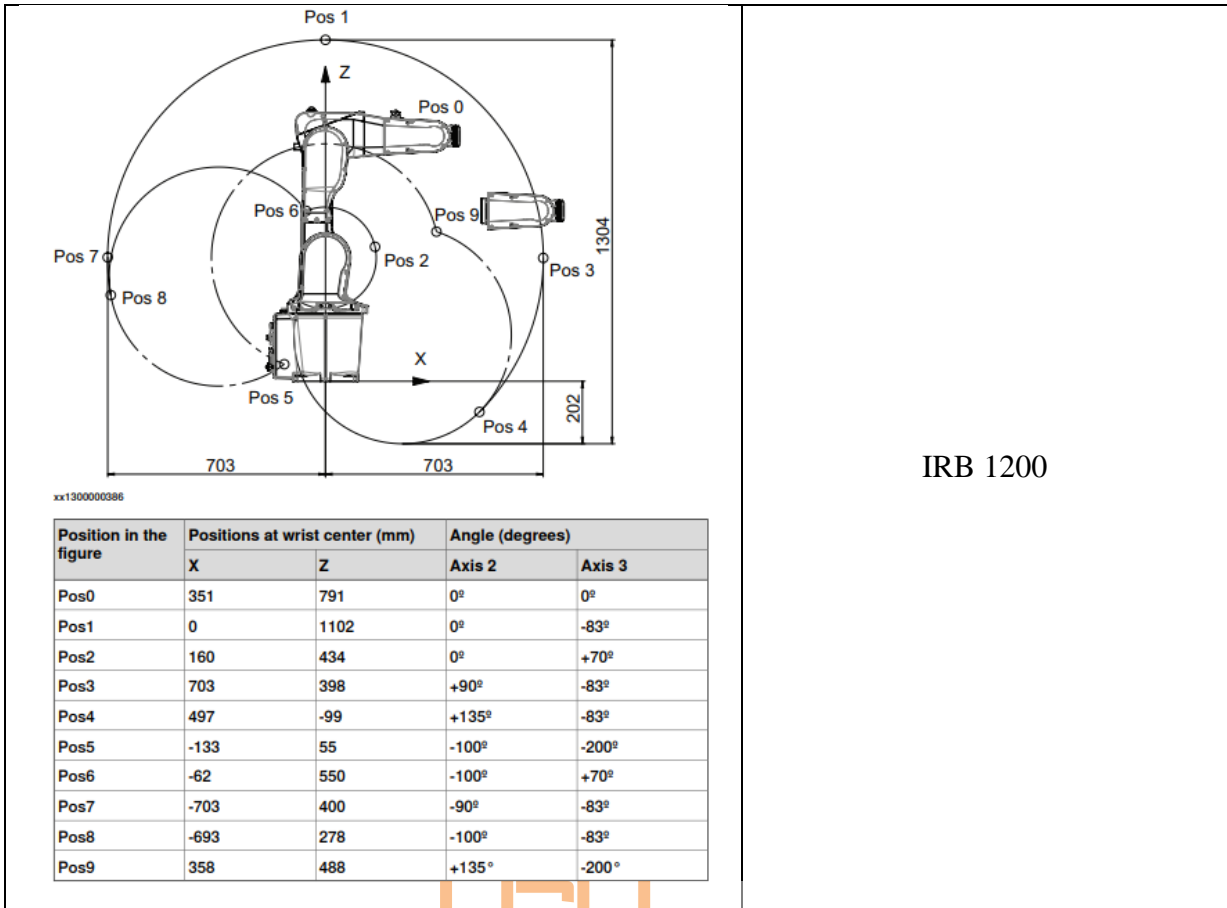
Table 7: Dimension comparison between robots

<p>Technical drawing of the GOFA robot arm. Dimensions shown: 110 (height of upper arm), 444 (total height), 265 (height of base), 470 (width of upper arm), 101 (width of end effector), and 80 (height of end effector).</p>	<p>GOFA</p>
<p>Technical drawing of the IRB 1300 robot arm. Dimensions shown: 519, 425, 90, 1099, 475, 1007, 240.6, 190, 2.20, 1.90, 45.5, 1.40, 1.20, 190, 110, 110, 110, 110, 110, 110.</p>	<p>IRB 1300</p> <p>Vietnamese-German University</p>
<p>Technical drawing of the IRB 1200 robot arm. Dimensions shown: 613, 451, 82, 42, 448, 967, 399.1, 210, 105, 269, 115, 47, 105, 210, 269.5, 185, 190, 162.</p>	<p>IRB 1200</p>

Working range comparison

Table 8: Working range comparison between robots

 <p>xx2000002410</p> <p>Positions at intersection point of axes 4-5-6 and angle of axes 2 and 3</p> <table border="1"> <thead> <tr> <th rowspan="2">Position in the figure</th> <th colspan="2">Positions at wrist center (mm)</th> <th colspan="2">Angle (degrees)</th> </tr> <tr> <th>X</th> <th>Z</th> <th>axis 2</th> <th>axis 3</th> </tr> </thead> <tbody> <tr> <td>pos0</td> <td>470</td> <td>899</td> <td>0°</td> <td>0°</td> </tr> <tr> <td>pos1</td> <td>0</td> <td>1216</td> <td>0°</td> <td>-68°</td> </tr> <tr> <td>pos2</td> <td>951</td> <td>265</td> <td>90°</td> <td>-68°</td> </tr> <tr> <td>pos3</td> <td>0</td> <td>-686</td> <td>180°</td> <td>-68°</td> </tr> <tr> <td>pos4</td> <td>-951</td> <td>265</td> <td>-90°</td> <td>-68°</td> </tr> <tr> <td>pos5</td> <td>-507</td> <td>-179</td> <td>180°</td> <td>22°</td> </tr> <tr> <td>pos6</td> <td>-230.2</td> <td>272.7</td> <td>180°</td> <td>85°</td> </tr> <tr> <td>pos7</td> <td>507</td> <td>-179</td> <td>180°</td> <td>-158°</td> </tr> </tbody> </table>	Position in the figure	Positions at wrist center (mm)		Angle (degrees)		X	Z	axis 2	axis 3	pos0	470	899	0°	0°	pos1	0	1216	0°	-68°	pos2	951	265	90°	-68°	pos3	0	-686	180°	-68°	pos4	-951	265	-90°	-68°	pos5	-507	-179	180°	22°	pos6	-230.2	272.7	180°	85°	pos7	507	-179	180°	-158°	<p style="text-align: center;">GOF A</p>										
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IRB 1200

Conclusion



After considering each aspect of all three robots, the GOFA is the most suitable option for being mounted and operated with the camera system. All the features of GOFA stay align the most with the requirements and constraints of the project. Further analysis is discussed below:

The handling capacity of the robot is 5kg, which is just enough for the camera system, even with additional weight for some lightweight lights and microphones. The entire cage system of the camera mounting is at most 1kg, so the camera's weight is the most significant proportion of all. However, most DSLR cameras, on average, weigh around 700g, while none exceed 1kg since these are designed for handheld users. Therefore, a payload of 11kg is not necessary. Furthermore, having a small load can significantly reduce the power consumption of the robot as well as the weight of the robot since it does not have to be equipped with more robust motors.

Reach is more critical if compared with weight. The camera system aims to have the biggest possible working range while also having a small robot for easy transportation. Out of the

three, it can be seen that the GOFA has a slight advantage of reach. Despite this, the main reason to choose GOFA is its structure. As mentioned before, instead of staying aligned, the camera will be positioned so that the lens' axis is offset from the robot's fifth link. The main reason is to reduce the robot's leverage arm length and the possibility of the joints going through singularities. Cartesian space and joint space are the two environments in which an industrial robot can be operated. In order to move an industrial robot, two sets of position-mode motion orders must be issued. For joint-space motion commands (often wrongly referred to as point-to-point commands), you simply give the desired set of joint positions, either directly or indirectly, and the robot moves by simultaneously and linearly translating or rotating each joint to the appropriate joint position. You must specify both the desired end-effector position and a desired Cartesian path when using Cartesian-space motion instructions (linear or circular). The robot controller must determine the inverse position and velocity kinematics of the robot in order to determine the required joint positions along the intended Cartesian path. There are configurations of the robot where this calculation cannot be done (division by zero), which are called singularities. This system can prevent singularity positions because the ABB robot's most common singularity position is when the 4th, 5th, and 6th axes are all 0° . So, by having an offset where the 5th axis is bent 90° , this problem can be neglected.



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Another reason GOFA is suitable is that it runs on 220V AC, Vietnam's standard household power supply. Also, the power consumption of GOFA is nearly twice as minuscule compared to IRB1200 and IRB1300. This happens because GOFA is a collaborative robot compared with industrial robots. The same reason explains why GOFA is also the lightest of all. A lightweight robot in the studio will be beneficial because it can be moved around easily to design new camera paths and shoot new angles.

While able to move around quickly, CRB 15000 is also installed with an uncomplicated programming wizard. Wizard programming is a new way to fill the gap of users who don't have much experience in coding (ABB, *Wizard easy programming: ABB Robotics* 2020)

Wizard programming is not the only feature OmniCore controllers have that IRC5 controllers do not. The OmniCore controller is much more compact and has a clean and smooth casing. The size of an OmniCore compact controller could be twice as small as the IRC5 compact. It also comes with a Flexpendant with a more reactive touch screen and better usability compared with the IRC5.

In conclusion, CRB 15000 is chosen due to its overall ease of use, operation, and flexibility, and its structure is efficiently compatible with videography applications.

3.2 Camera and lens

3.2.1 Camera

Digital cameras are cameras that capture pictures in digital memory. In other words, the camera contains a sensor that, when the user snaps a picture, is exposed to the scene via a mechanism, resulting in capturing and storing the image on an SD card. Digital cameras are mostly used today, replacing most cameras that take photos by exposing photographic film to lights. Digital cameras are the primary tool for taking pictures and shooting videos nowadays. Digital cameras for consumers interested in performing these tasks are divided into digital single-lens reflex (DSLR) and mirrorless cameras. Both types still find a way to expose the sensor, but how each type does it separates one from another. DSLR has a reflecting mirror that will flip up and expose the sensor whenever users take a photo. When they don't, the reflecting mirror will reflect the scene onto a view-finder to give the user a first look at how the scene in front of them will be composed after they press the button.

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On the other hand, a mirror-less camera will continuously expose the sensor to the scene, and the scene will be displayed as a "live view" on an LCD screen or a digital view-finder. By this concept, the DSLR is usually bigger and heavier, while the mirrorless has shorter battery life. In whatever way, both cameras are the target this project wants to achieve. Their focal adjusting system stays the same, which can be controlled through a turning mechanism located on the lens. By turning it, the lens inside will move and thusly change the focal length. Some cameras have better autofocus systems than others. However, this project aims to support those who are not as good as others. At the same time, the other can also benefit from this project because having complete control of the focal length and controlling it with the camera path can bring a lot more variation and creativity into the shots.

Nikon D5200 is the chosen camera for this design process. It is an entry-level DSLR camera with a weight of 555g and dimensions of approximately 129 x 98 x 78 mm, based on what is mentioned in the datasheet (Nikon, 2012). The camera comes with an autofocus sensor with 39 focus points. It takes about 1-3 seconds for the camera to find focus and its reaction rate for the

camera to know the image it is looking at is out of focus is low, in a way that it will keep idling until an entirely different scene is introduced. Therefore, the project aims to support these low-level autofocus cameras to perform efficiently without needing autofocus. Nowadays, some new cameras have a stabilization system inside the lens or the camera's sensor to keep the shots from jittering. This camera, however, does not possess this feature; therefore, the judder of the system will be reflected through the video clips produced by Nikon D5200 mounted on the GOFA robot. From that, further research and improvement will take place in order to reduce this factor to a minimum because judder is not favorable in the filming industry

3.2.2 Lens

A camera lens is a device consisting of a series of concave and convex glass that both converge or diverge light that the camera receives and focuses it to a focal point. This focal point is calculated to be placed precisely on the film strip if the camera is an old-generation film camera or on the digital sensor from the digital camera. However, there are an infinite number of light rays being reflected from an object to the camera sensor, parts of the object that has light rays go through the lens and manage to converge directly onto the focal point will be shown to be in-focus on the image. In contrast, those that do not will be perceived as blurry or out-of-focus. Hence the focus ring is born to help to choose which part of an object the user wants to focus on and parts that the user does not. By a simple Heli-coil mechanism, turning the focus ring will move the focusing lens or the lens focusing group. Thus, it allows different light rays that were not in focus before to converge onto the digital sensor; the focus is achieved.

Some lenses that support autofocus have a servo that drives this part of the lens, but some are better than others. So again, this project tries to extend our target customer by supporting cameras or lenses with a focus system that is inefficient for fast movements.

The chosen lens for this project is YongNuo 50mm f/1.8 lens. Its datasheet (B&H, *Yongnuo YN 50mm f/1.8 lens for canon EF* 2018) shows that this 120g lens is a prime lens, meaning that the distance between the lens and the sensor remains at a constant of 50mm. With a fixed focal length, the lens cannot zoom in or out to a scene but, in return, have a small and compact design. The diameter of the lens is 73mm, while its length is 55mm. This parameter will be considered when designing a gear that fits with the focal ring. After measuring the thickness of

the focal ring, the result is 10.8mm. From this, the overall dimension of the focus ring is 73mm in diameter and 10.8 in thickness.

Another important measurement to consider is the angle range of the focal ring, meaning the coverage angle where the focusing lens goes from closest to farthest away from the camera. The result of the measurement is 140°.

3.3 Motor selection and gear transmission

3.3.1 Introduction

To control the camera's focal length, a gear is used to wrap around the mechanism generally used on the lens to control the focus manually. From that, a motor that can rotate to any desired angle commanded by Robotstudio will be in charge. A transmission box is necessary if the motor's angle range is smaller than that of the lens focal ring or the lens mechanism requires significant force to move. However, most focal rings on the camera lens are very light regarding the moment of inertia. This is because inside, a Heli-coil helps move the lens when turning the focus ring. The Heli-coil has reduced the force to move the lens by prolonging the distance to move it. This is the principle of work. Therefore, the only parameter to consider is the focus ring range compared with the servo rotation range. The first part of this section is to choose motors, and the second part will cover gear transmission design.

3.3.2 Motor selection

A motor that can precisely control the rotation angle based on a signal is the definition of an RC servo motor. These cheap and mass-produced rotary actuators can output a specific angle based on the PWM signal. PWM, or Pulse Width Modulation, is a method that creates pulses with changing widths to simulate the amplitude of an analog input signal, which will not fit this system without a controller that can translate the analog signal to PWM. However, this will be discussed later. The vital step before choosing the suitable servo motor is considering all the criteria. This focusing system will need a motor with a slight angle step and the most extensive possible rotating range. It ensures that the focus ring can be moved at a small distance; thus, missing positions could be reduced. In addition, having a high rotating range is preferable since it will result in a simple gear design where the gear that attaches to the servo is smaller than the gear on the focus ring if the motor's rotating range is greater than the focal ring's. The other

way implies that the servo gear should have more teeth (thus more significant) than the lens gear. This would lead to a rambling design; a 4-gear transmission box would be used instead. However, to keep the design from too many components, 4-gear transmission should be avoided.

Conversely, these first two criteria can often be seen in expensive or large motors. This focal system should therefore consider the motor's size and weight based on the previously discussed constraints. In summary, there are these criteria:

- Small angle step
- Large rotating range
- Cost-efficient
- Lightweight

Here are two options that fit these criteria:

SG90

SG90 is a low-cost plastic RC servo that most students use for their robotic arm projects or projects requiring accurate rotating angle output. Here is its specification that can be found on the SG90 datasheet (TowerPro, n.d.)

- Weight: 300g
- Dimensions: 23 x 11.5 x 24 mm
- Stall torque: 1.8 kg.cm
- Rotate angle: 180°
- Operating voltage: 4.8 ~ 6 VDC
- Operating speed: 0.1s/60°
- Gear type: plastic gears
- Pulse width: 500 – 2500 μ s
- Dead band width: 10 μ s



Figure 15: Tower Pro SG90 (TowerPro, n.d.)

The angle step is not given but can be calculated using pulse width and dead bandwidth. Pulse width is the elapsed time between high and low electrical signal pulse. PWM drives will produce a high frequency of these signals that will look like a train of square-wave pulses, and the “width” of the square, known as Pulse width, will control what angle the servo will

produce. In this case, 500 μs will produce 0° while 2500 μs will produce 180°. The relationship is linear, so the pulse width of 1° can be calculated as follow:

$$\frac{2500\mu\text{s} - 500\mu\text{s}}{180^\circ} = 11.111 \mu\text{s}/^\circ$$

Dead band width means that if a pulse is less than 10 μs , the motor cannot pick up the signal, thus not moving. Seeing this dead bandwidth is close to the 1° pulse width, it can be concluded that the step angle of this motor is roughly 1°.

Hiwonder LD-27MG

LD-27MG from Hiwonder is a liable RC servo mainly used for robotic arms or RC robot cars. It costs more than SG90 but for the price range this motor yields. The following specification can be found on the Hiwonder LD-27MG datasheet: (Hiwonder, 2020)

- Weight: 66g
- Dimensions: 54.5 x 20 x 47.5 mm
- Stall torque: 20kg.cm
- Rotate angle: 270°
- Operating voltage: 6 ~ 7.4 VDC
- Operating speed: 0.2s/60°
- Gear type: metal gears
- Pulse width: 500 – 2500 μs
- Step angle: 0.4°



Figure 16: Hiwonder LD-27MG (Hiwonder, 2020)

Conclusion

Comparing the two suggests that Hiwonder LD-27MG is more compatible with what the project is looking for. However, the SG90 also satisfies all the criteria. The angle range of SG90 is 180°, which is larger than the focal ring's range, and a 1° step angle is efficient enough. Therefore, the SG90 was first chosen for testing.

However, a problem occurred that shows the fundamental problem of SG90 that the criteria of choosing motors don't cover. After purchasing, the motor was tested with the microcontroller programmed just to run the motor only and see how the motor reacted when being applied with different PWM signals (Further details of the test can be found in the paper). The actual step angle of the motor was more prominent than 1°, and the motor shaft shook slightly every time

it went to any angle. A second SG90 was bought, but the same problem still occurred. Further analysis of the motor speculated that this motor's plastic gears are the problem for these two problems. It could be because of improper manufacturing or the material problem that the calculated step angle is smaller than the actual angle. The gear ratio of these gears could also multiply the step angle into a more significant angle. Plastic material could potentially be the reason for backlash, which is when the gap between two teeth is too considerable that the servo shaft seems to be jitter or unstable. These factors make a metal-gear motor adequate, which is why the LD-27MG is selected as the focus system's motor.

3.3.3 Gear transmission calculation

Gear ratio is the ratio between the number of teeth of the driving gear over the driven gear or the ratio between their speed. However, the ratio can also be applied to the traveling angle of each gear. For example, a 10-teeth gear meshed with a 5-teeth gear will have a gear ratio of 0.5, with the 5-teeth being the driving gear and the 10-teeth being the driven one. It can be realized that the 5-teeth has to travel two revolutions for the 10-teeth to one. Alternatively, it can be said that the driving gear has to travel 720° for the driven gear to travel 360° , and this angle ratio is the reverse of the gear ratio.



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With this, a formula between the gear teeth and the gear angle can be derived:

$$\frac{z1}{z2} = \frac{\theta2}{\theta1}$$

$z1$: number of teeth of the driving gear

$\theta1$: rotating angle of the driving gear

$z2$: number of teeth of the driven gear

$\theta2$: rotating angle of the driven gear

Since the rotation range of the lens is 140° (driven gear) and the rotation range of the motor is 270° (driving gear), the equation will become:

$$\frac{z1}{z2} = \frac{\theta2}{\theta1} = \frac{140}{270} = 0.518$$

Now there could be many options of teeth that will satisfy this ratio. In order to find the correct teeth for each gear, gear module is introduced. Gear module is an indication of how big or

small a gear is. It is a ratio between the reference diameter divided by the number of teeth. Two gears can only mate if they share the same module.

$$m = \frac{d}{z}$$

A look-up on many companies that manufacture camera equipment suggests that their standard module for gear equipment is 0.8 (mm/teeth) (32 0.8 module). When this standard is applied, the last parameter to consider is the reference diameter, also known as the diameter of the reference circle. The reference circle locates between the top and the root of the gear teeth. 2 gears are considered mating if their two reference circles are tangent. This position ensures that there will be no slippage because the teeth of the two gears are fully engaged. The condition to find the reference diameter is that this diameter must be larger than the diameter of the lens, which is 74mm. An inequation can be derived.

$$d = m \times z = 0.8z > 74$$

$$\Rightarrow z > 92.5 \text{ teeth}$$

There is a lower bound for the number of teeth, but the upper bound can only be considered through the geometry of the gear because more teeth mean that the gear will be bigger. On Solidworks, there is a toolbox with the standard gears, and it allows configuration for any modification of these parameters: module, number of teeth, pressure angle, face width... To open this toolbox, go to Design Library > Toolbox > DIN > Power Transmission > Gears and choose Spur gears.

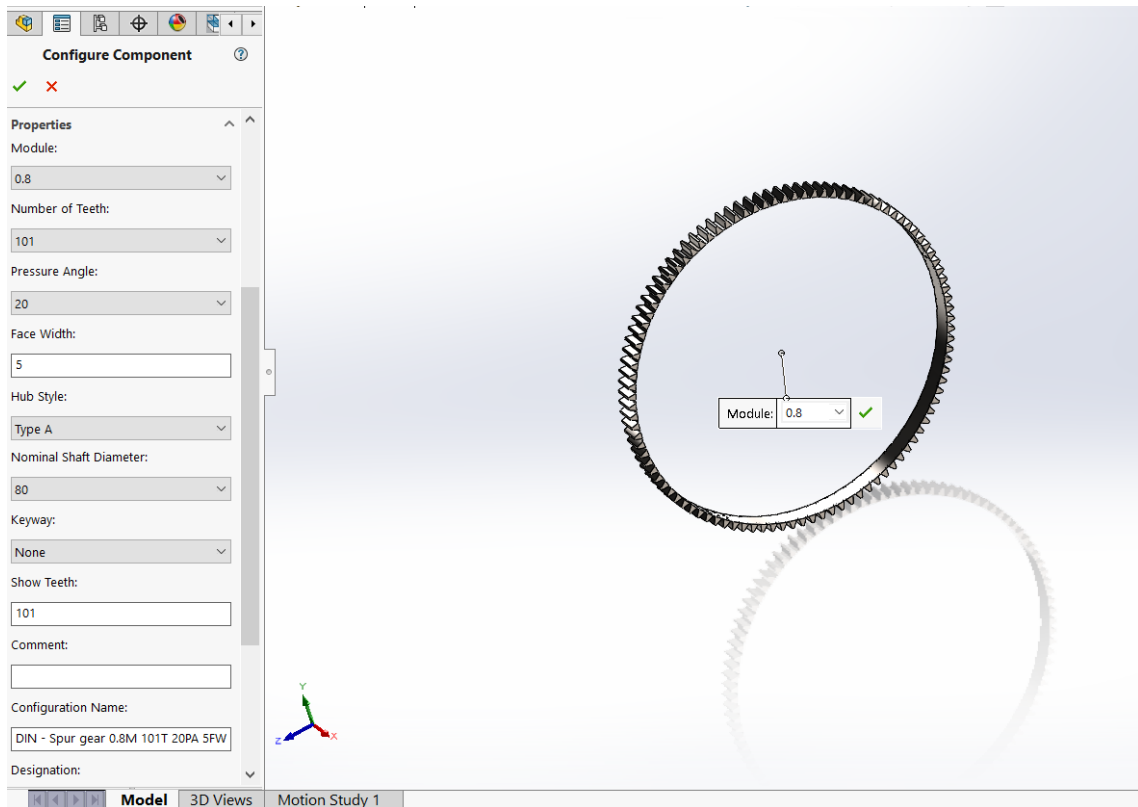


Figure 17: Configuring gear standard on Solidwork



By using Solidwork as an assistance, teeth number of 101 for the focal ring ensures the right thickness of the gear. From $z_2=101$, z_1 can be found

$$\frac{z_1}{101} = 0.518 \Rightarrow z_1 = 52.37 \approx 53 \text{ teeth}$$

After rounding up, the real gear ratio is calculated:

$$i_{eff} = \frac{z_1}{z_2} = 0.52475$$

With the real gear ratio calculated, the step angle of the servo after going through the gear is discovered:

$$i_{eff} = \frac{\Delta \theta_2}{\Delta \theta_1}$$

$$0.52475 = \frac{\Delta \theta_2}{0.4}$$

$$\Delta \theta_2 = 0.21^\circ$$

Step angle is reduced by half when being transmitted through this gear ratio.

3.3.4 Gear transmission design

To make this gear transmission flexible for all camera lenses where each focal ring can be located uniquely, the sliding mechanism parallel to the axis of the lens is utilized. This system will hold the motor and driving gear, which can move freely along the axis of the lens. This design is believed to satisfy this criterion:

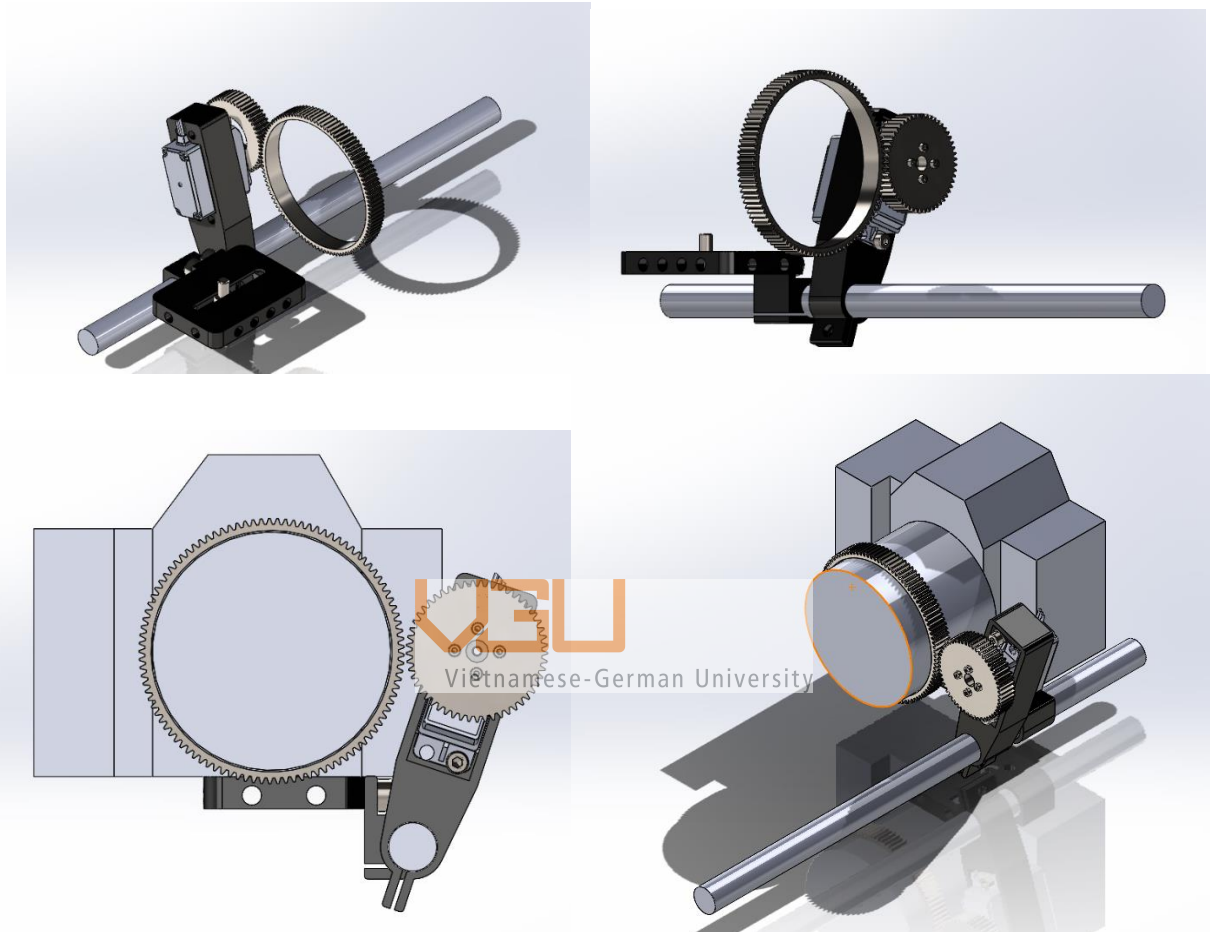


Figure 18: Gear transmission system

3.4 Focus control system

3.4.1 Introduction

The focus control system's primary function is to convert the analog signal from the IO device to PWM for the servo. The RC servo motor and microprocessor in this setup both run on batteries. In order to wire the ABB IO device to the microcontroller and link it to the robot controller, a thorough analysis of the devices is required. A small electrical box that will be placed close to the robot's sixth joint will house the entire system.

3.4.2 Microcontroller

Atmel created the ATmega328P microcontroller. This is the chip that powers the well-known Arduino test boards. This section will focus on the Arduino Uno specifically. The ATmega328P datasheet (Atmel, 2015) is the source of all the values stated in this paragraph. Based on an 8-bit architecture, the Atmel chip. The microcontroller primarily functions as a signal receiver for the IO device from ABB, sending signals in PWM to the servo. There are more input/output pins available than the servo needs—there are 26 total.

The website's documentation is quite well organized, which is one benefit of using Arduino. Eagle files and schematics are given for every microcontroller. Along with a fair amount of official documentation, there is also a huge amount of user-generated documentation in the form of lessons, videos, and advice. These message boards are incredibly well-liked and have a large and active online fan following that includes both amateurs and experts. Online resources frequently contain completely functional code for a variety of operations. Well-commented open-source code that is welcomed to be utilized by whoever needs it as long as proper acknowledgment is given is not hard to come by. A simple search finds that there are libraries devoted to using an ATmega328P to control stepper and servo motors. Particularly useful for programming the Focus control system. Here is a list of specification of the controller.

Table 9: Specification of the microcontroller (Atmel, 2015)

Board	Name	Arduino UNO R3
Microcontroller	ATmega328P	
USB connector	USB-B	
Pins	Digital IO pins	14
	Analog input pins	6
	PWM pins	6
Power	IO voltage	5V
	Input voltage	7-12V
	DC Current per IO pin	20mA
Memory	ATmega328P	2KB SRAM, 32KB FLASH, 1 KB EEPROM
Dimensions	Weight	25g
	Width	53.4mm
	Length	68.6mm



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3.4.3 IO device from ABB

IO device is a hardware that used to communicate with a computer by a human operator or other systems. IO devices can provide data to a computer (output) and receive data from a computer (input). The modular, small-footprint, and scalable ABB Scalable I/O system is made up of base devices, which are the bare minimum configuration, and add-on devices (ABB, *Application manual - ABB Scalable I/O* 2019). Any combination of add-on devices is supported, and each base device can operate up to four add-on devices while maintaining performance. Main communication between the robot controllers and the digital base device is Ethernet/IP communication protocol. Ethernet/IP (Ethernet Industrial Protocol) is a network communication standard particularly for automation control purposes that can handle massive amounts of data rates, allowing devices to communicate with one another in real-time.

The main base device is required for the entire system including the add-ons to be detected and configure. The base device, also known as DSQC 1030, is a digital base with 16 digital inputs and 16 digital outputs. Power supply for this digital base ranges from 20.4 – 28.8 VDC. To

connect the digital base to the controller, DSQC 1030 must connect to the power supply and Ethernet, from then the device can be configured. Configuration is a process of changing the IO device's IP address on the controller network, because one robot controller could connect to up to 20 devices, each should have their own IP address.

2 ABB IO devices communicate through an optical module located on the side of the device, by simply fit the add-on device to the guide rails on the right of the base device, the two optical ports will be aligned and thusly connected. For both the devices to activate their optical communication, they will have to be supplied in power. There are two power sinks in a device, logic power and process power. While the logic power is needed to run the IO device, process power is used to power all the outputs on the device. But this only applies for the base device DSQC 1030, the rest of the add-ons both power sinks are on the same port. All the devices are supplied by an external 24VDC power, all the logic and process power are connected in parallel as seen in the picture



Figure 19: Wiring on IO devices [Own design]



Figure 20: [Vietnamese General University]

While the base device only supports 16 digital output pins and 16 digital input pins, another analog add-on will be required. DSQC1032 is an analog add-on that support 4 analog outputs and 4 analog inputs. List of specification can be found below:

Table 10: DSQC 1032 specification (ABB, Application manual - ABB Scalable I/O 2019, p.43)

Description	Data
Output range	0-10V
Resolution	12 bits

A 12-bit resolution means that the range 0-10V can be divided and presented through 4096 different numbers. With that the increment is calculated to be 2.4mV. This step voltage is more than sufficient to control the motor's angle.

3.4.4 Circuit diagram

The RC servo will connect to the 9th digital pin, this pin in the datasheet mentions it will output PWM signal. For the IO device, Analog output 1 from the IO device will connect to A0 pin of the Arduino UNO. Because the analog input of the UNO can only handle signals less than 5V and the analog output of the IO device produces signals from 0-10V, therefore a voltage divider is applied to divide this voltage by 2. The voltage divider formula indicates that

$$V_{out} = V_{in} \times \frac{R2}{R2 + R1}$$

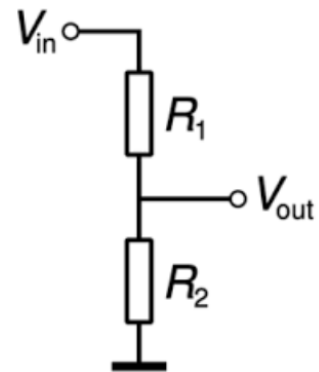


Figure 1: Voltage divider diagram

For V_{out} to be twice as small compared to V_{in} , $R2$ should equal to $R1$. In Proteus (Labcenter Electronics, *Proteus Design Suite* 1988), an electrical simulation software, $R1$ and $R2$ is chosen to be $1k \Omega$. So, whatever the voltage output from the IO device, it will be divided by half, thus stay within the voltage limit of UNO's analog input.

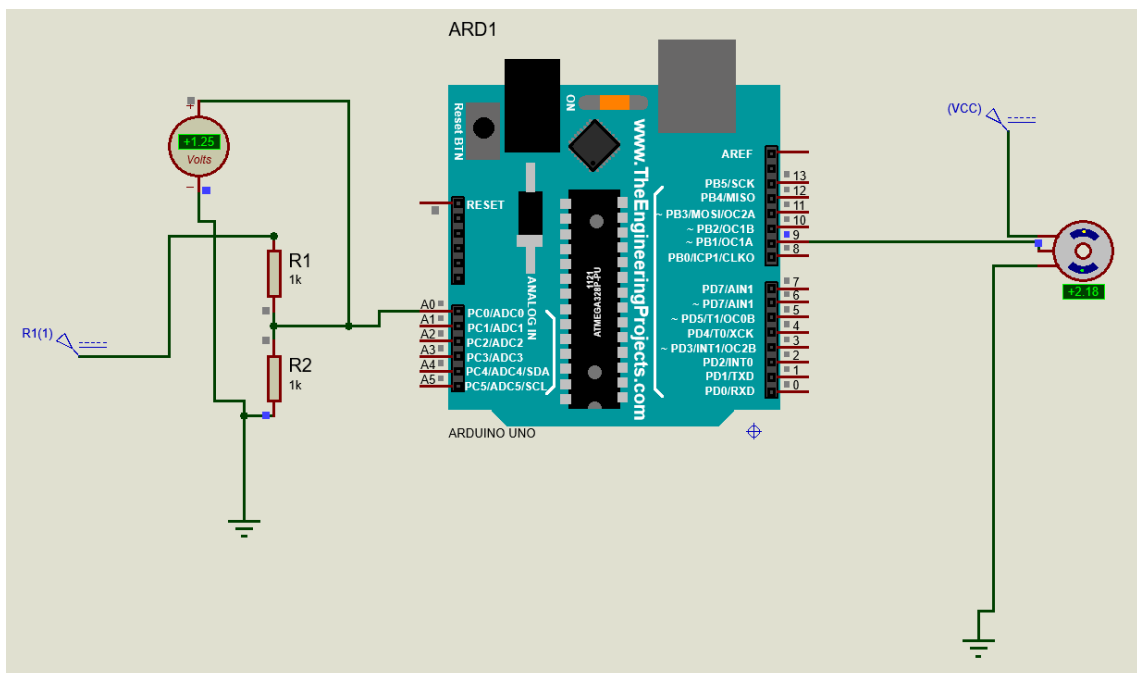
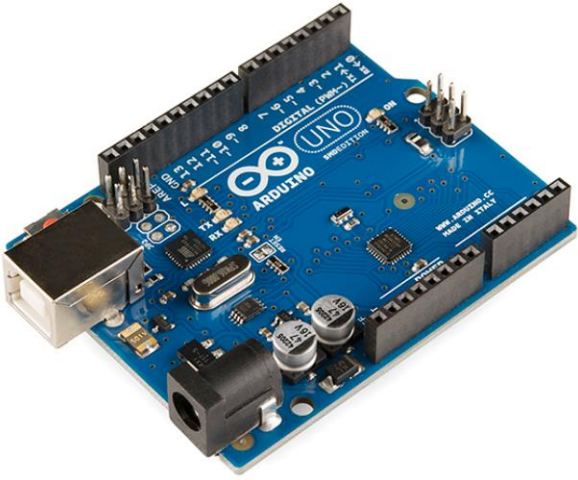
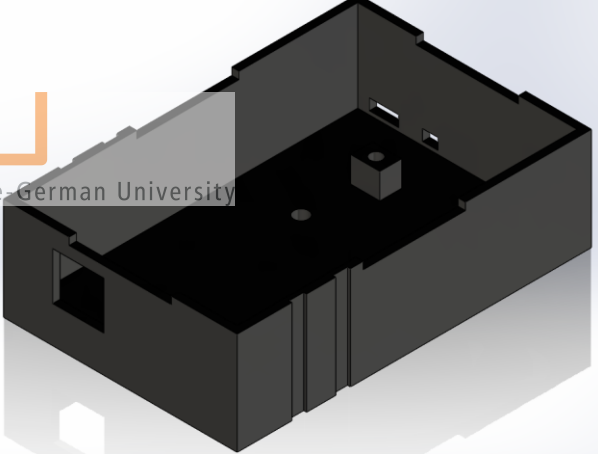



Figure 21: Circuit design in Proteus [Own design]

3.4.5 Set-up electrical components

List of components

Table 11: List of electrical components

Components	Picture
Arduino UNO	 A blue Arduino UNO R3 microcontroller board. It features a USB Type-B port, a DC power jack, a reset button, and a multi-pin header. The board is populated with various electronic components including a microcontroller, capacitors, and resistors.
Electrical case	 A black, rectangular electrical case with a hinged lid. The case is designed to house electronic components. A watermark for 'VGU Vietnamese-German University' is visible over the image.
18650 Batteries	 A single cylindrical 18650 Li-Ion battery. The battery is green with a black end cap. The label on the battery includes the model number 'NCR18650B', 'Li-Ion MH12210', and safety warnings: 'WARNING: BATTERY MAY EXPLODE OR FIRE IF MISTREATED. DO NOT DISASSEMBLE OR EXPOSE TO FIRE. DO NOT CHARGE EXCEPT SPECIFIED CHARGING CONDITION. DO NOT HEAT ABOVE 55°C OR SHORT CIRCUIT. MADE IN JAPAN. DO NOT CRUSH OR ABUSE.'.

Batteries case



M-M, M-F jumper wire



Final assembly

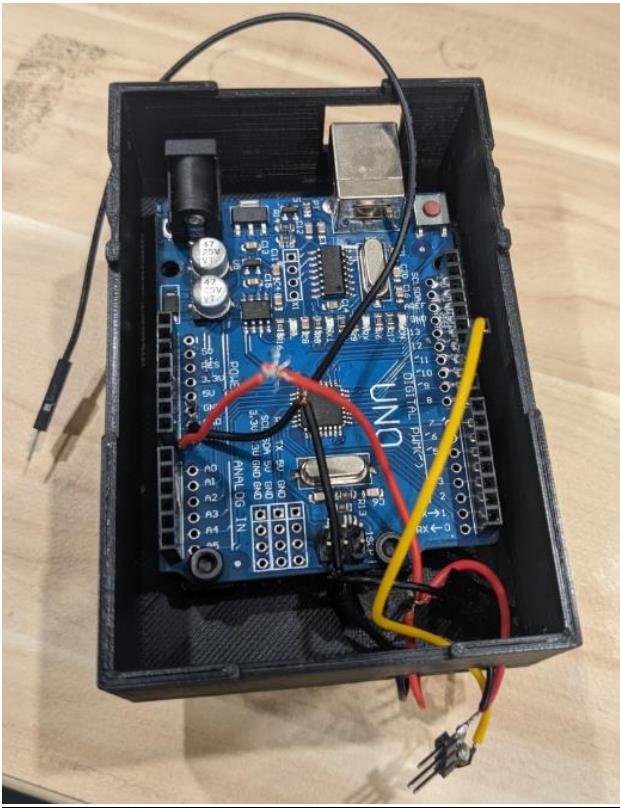


Figure 22: Electrical housing



Figure 23: Battery case under electrical housing



Figure 24: Components of focal changing system

3.5 Camera mounting system design

3.5.1 Camera casing

Four rods make up the camera housing, designed to securely support the camera and the focus mechanism on the robot. To be able to adjust the height and width of the casing to fit a variety of digital cameras, the construction is built with sliding slots rather than permanent holes. The bolts and nuts are used to hold the structure together, but when the bolts and nuts are untightened, they can slide into the slots to modify the case's dimensions. There are some essential criteria that the camera case should cover:

- Camera case structure should not hinder the focus system motion, or get in the way of the buttons located on the camera
- The camera case should be lightweight but steady
- The camera case should be painted black to reduce the reflection of colors.

The design is established

Rig rod 1

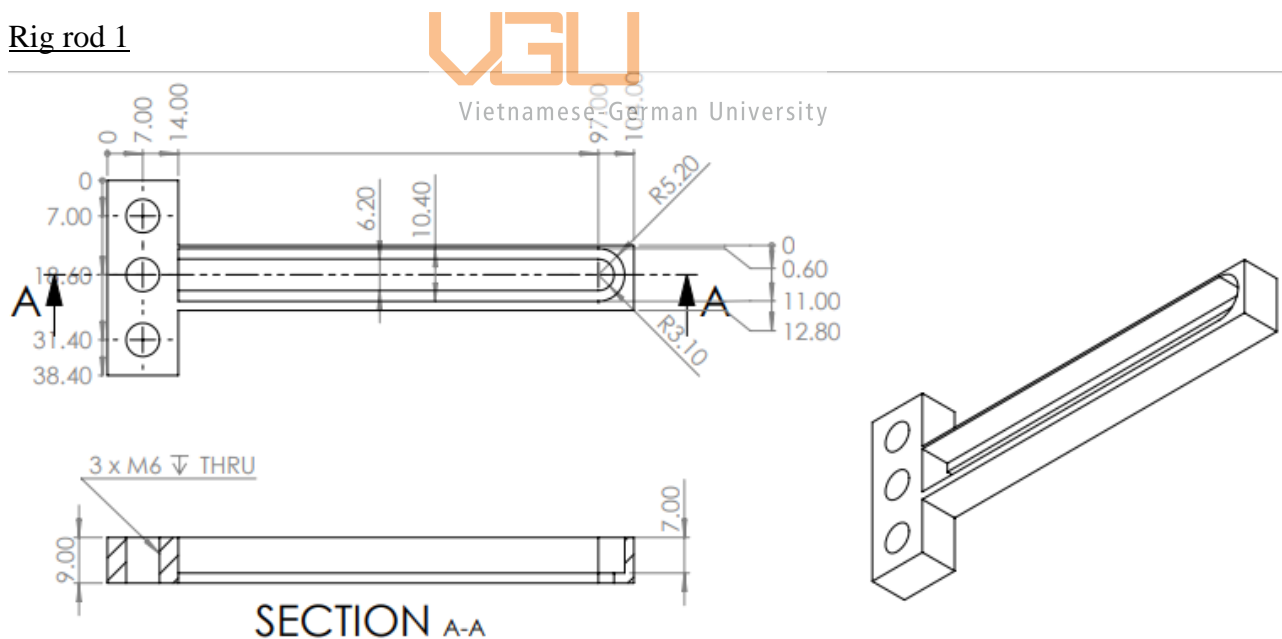


Figure 25: Rig rod 1 2D drawing

Rig rod 2

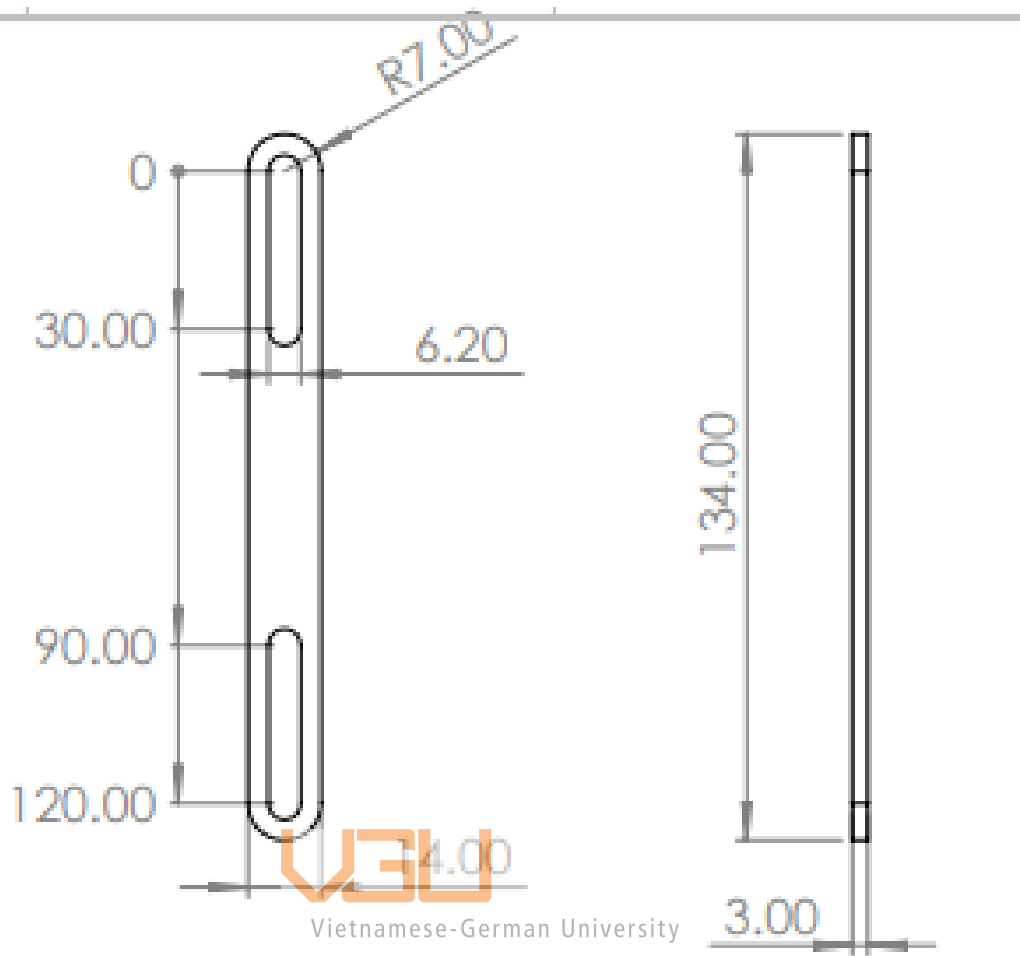


Figure 26: Rig rod 2 2D drawing

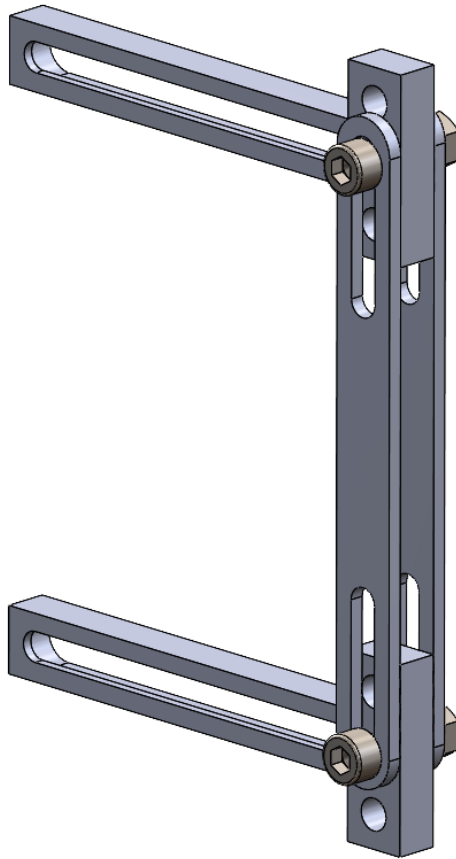


Figure 27: Assembly of rig rods

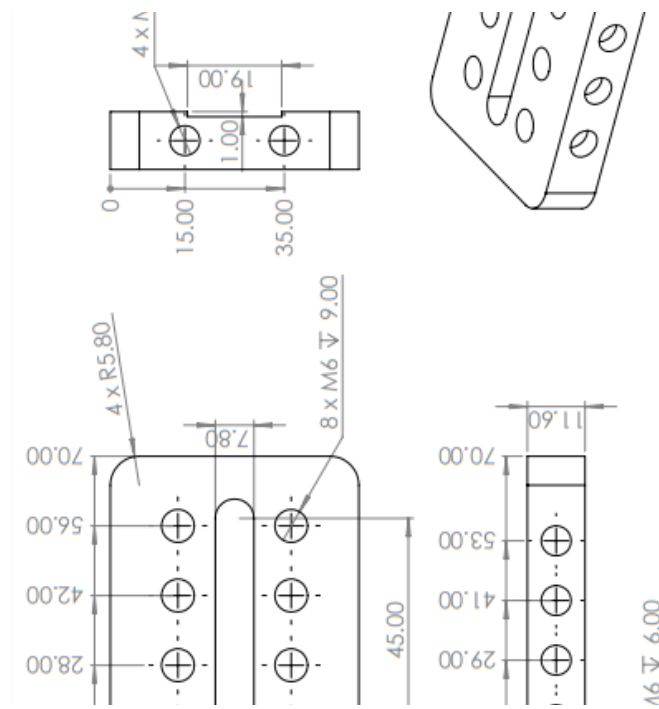
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3.5.2 Camera upper and lower plates

The top and lower plates are in charge of the camera's connection to the mounting system and stability. The standard holes are used because they will be used to mount additional equipment and the RC servo. Most cameras' equipment uses M6 bolts, which are the standard bolt.

The lower base plate shall have a sliding slot for the 1/4" -20 camera screw to tighten the camera to the base plate. The upper plate is where the robot will connect to the entire system. Again, the system will have a robot connector, which this part will have one face following the design of the robot's flange, while the other will be holes for bolts to connect the connector to the upper plate.

Upper plate



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Lower plate

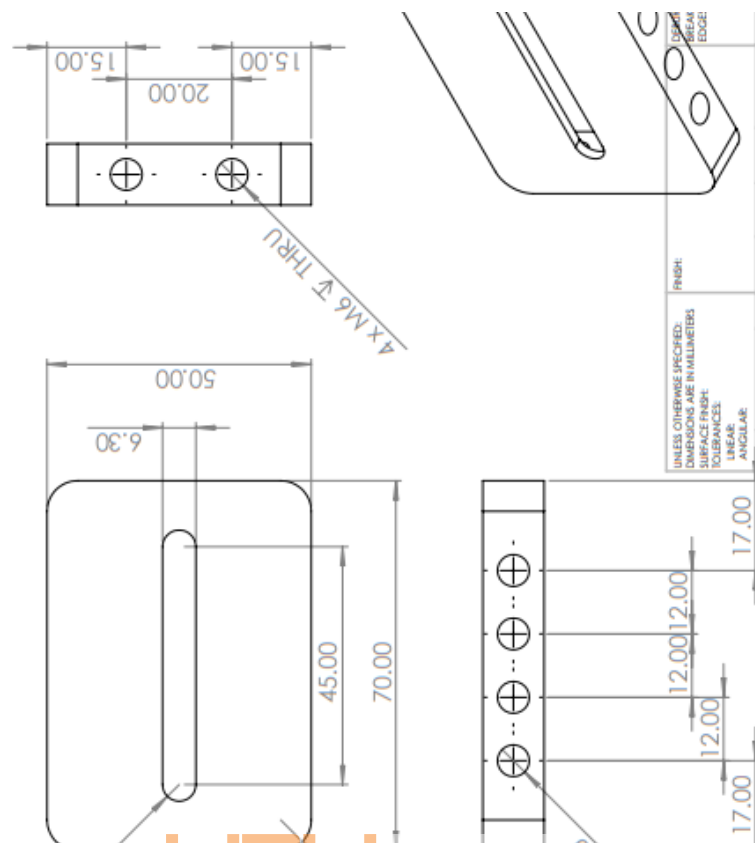


Figure 29: Lower plate 2D drawing

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Robot connector

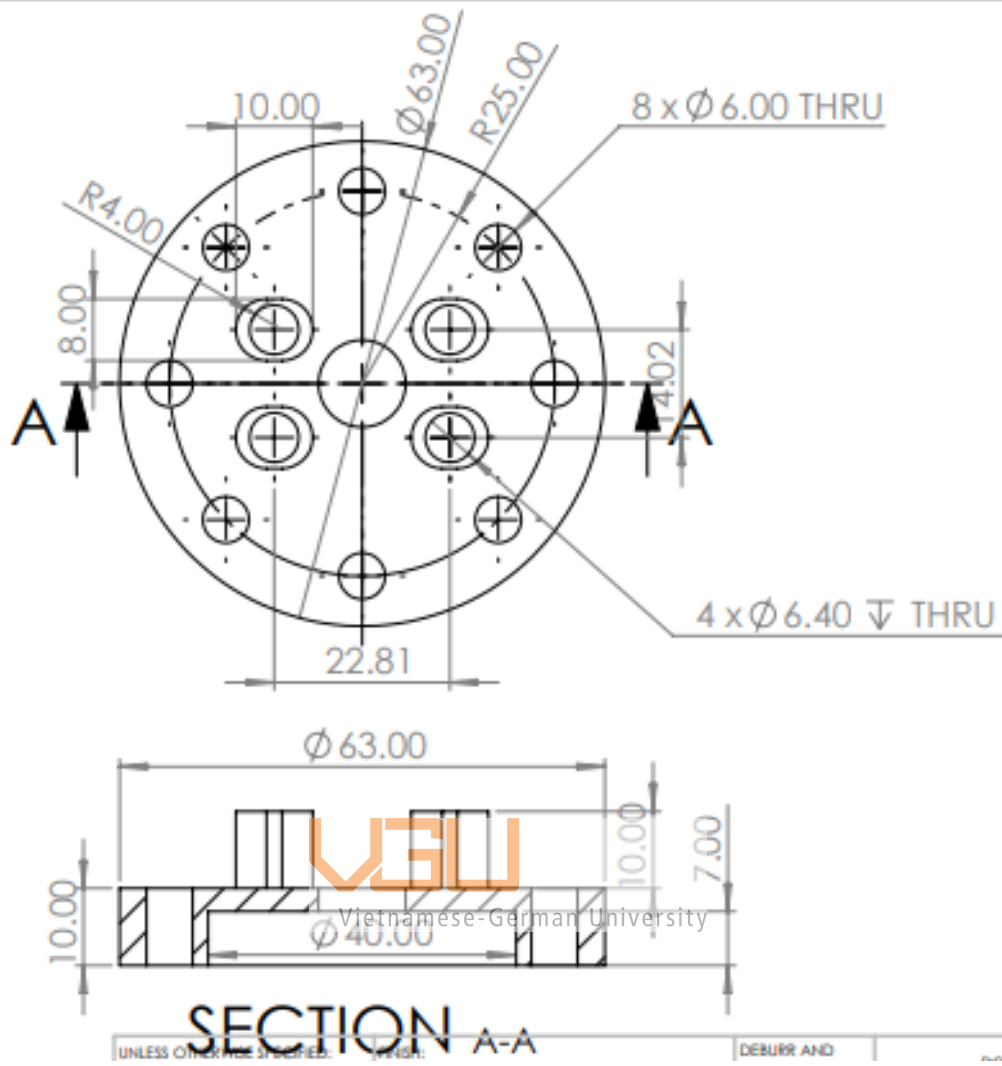


Figure 30: Robot connector 2D drawing

Final design of upper, lower plate and robot connector

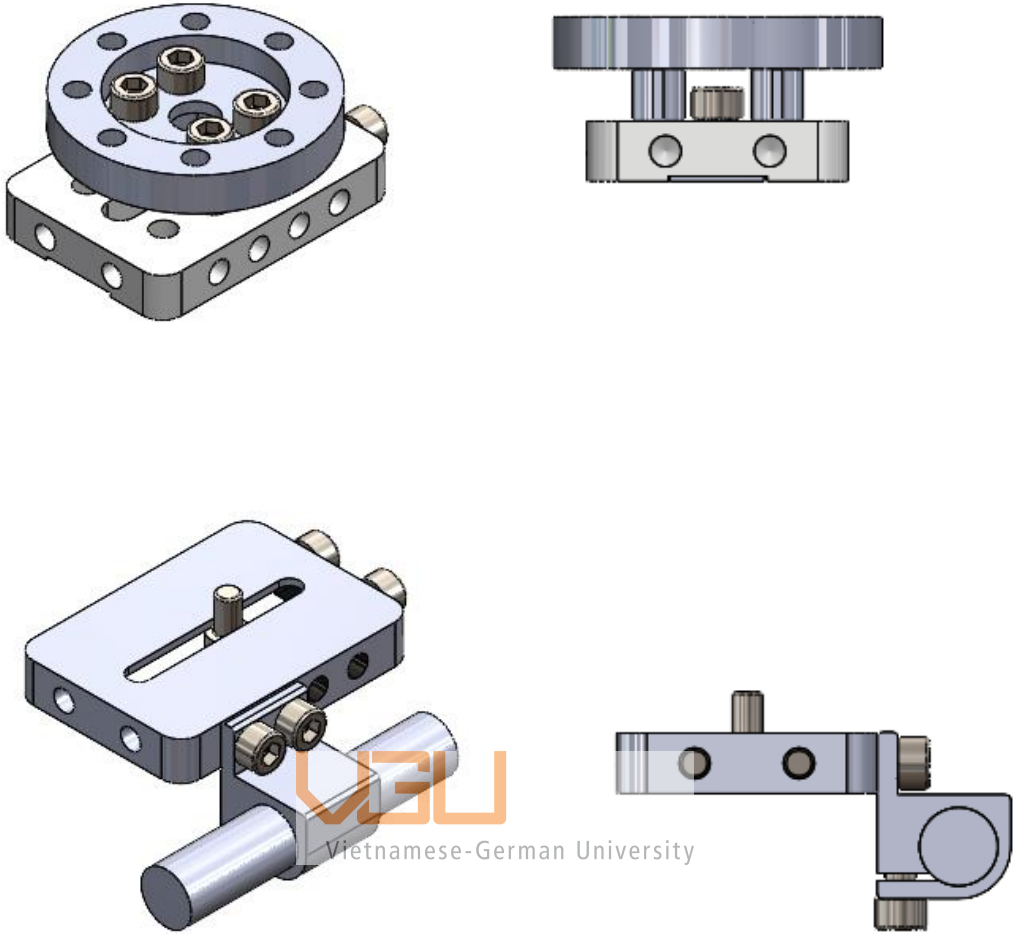


Figure 31: Isometric and front view of upper and lower plate

Final design of the camera case



Figure 32: Final design of camera case

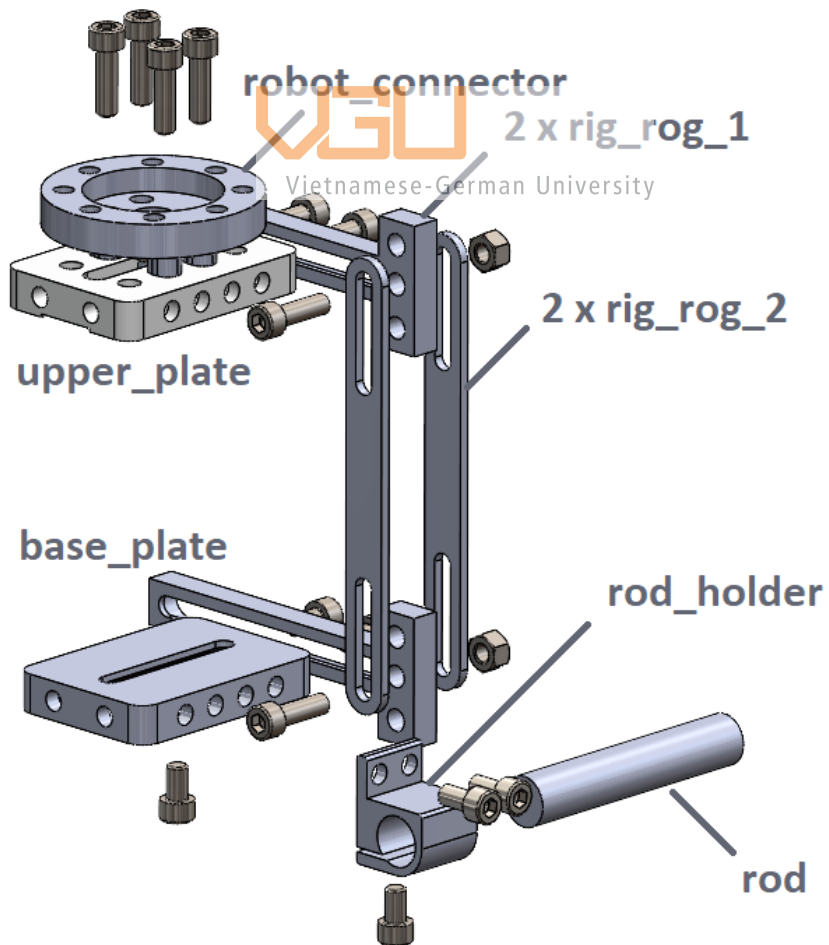


Figure 33: Components of camera case

3.5.3 Final design of entire system

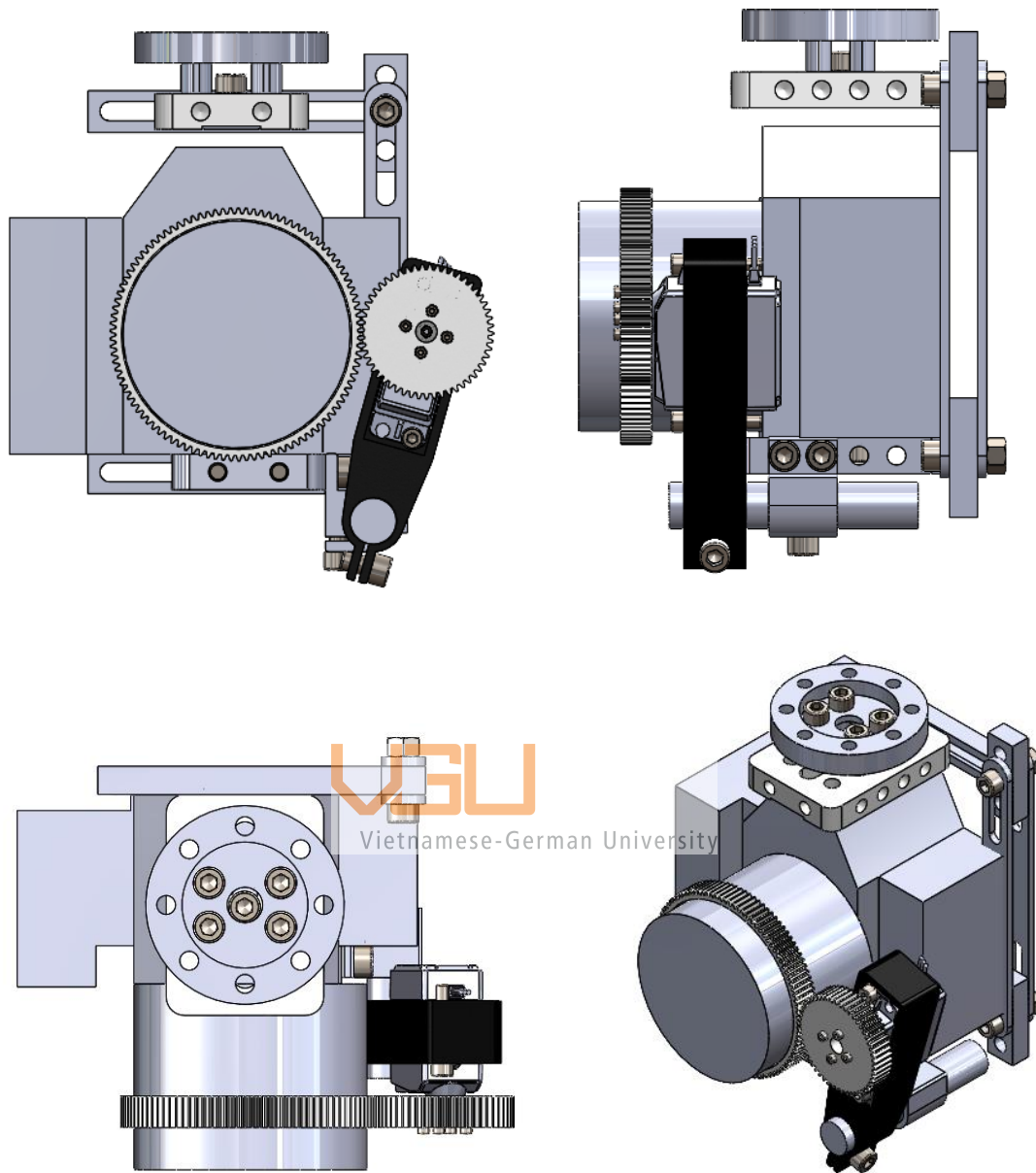


Figure 34: Four views of the whole system (3D model)

3.5.4 Material selection

Stainless steel is a popular material for structures because it meets the requirements of being both lightweight and sturdy. AISI 321 Annealed Stainless Steel, to be precise (SS). On Solidwork's library, the specification is available.

Table 12: AISI 321 Annealed Stainless Steel (Dassault Systemes, Solidworks 1995)

Property	Value
Elastic Modulus	1.93 N/m ²
Poisson's Ratio	0.27
Tensile Strength	62 x 10 ⁷ N/m ²
Yield Strength	23 x 10 ⁷ N/m ²
Thermal Expansion Coefficient	1.7 x 10 ⁻⁵ 1/K
Mass density	8000 kg/m ³
Hardening factor	0.85

3.5.5 FEM analysis

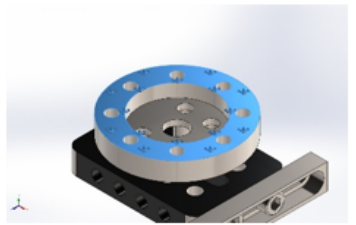
Finite Element Method solves differential equations that arise when computing displacements, stresses, and strains in a structure under specified loads. By discretizing the physical events into tiny elements, finite element analysis replicates the phenomena using mathematical numerical approaches. This tool is primarily used with 3D design software after the user has finished designing. By doing a thorough FEM analysis, the researcher can better understand the part's behavior when being applied loads.

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The first step of doing a FEM analysis is ensuring all the parts are correctly mated. The computer will see this mating as interactions between parts. Then, it is determined how this assembly fixes and what load is being applied to it. For this project, the robot connector's top surface is considered a fixture, and the load is the weight of the camera applied on the surface of the base plate. Then one should determine what the mesh for this model is. It can be coarse or fine. Depending on the computing ability of the computer, coarse mesh is chosen in this case.

Below are all the parameters for this analysis.

Load and fixture

Fixture name	Fixture Image	Fixture Details		
Fixed-1		Entities: 1 face(s) Type: Fixed Geometry		
Resultant Forces				
Components	X	Y	Z	Resultant
Reaction force(N)	-5.53513e-12	5.43888e-06	-1.43929e-12	5.43888e-06
Reaction Moment(N.m)	0	0	0	0

Load name	Load Image	Load Details
Pressure-1		Entities: 1 face(s) Type: Normal to selected face Value: 0.00172314 Units: N/m ² Phase Angle: 0 Units: deg

Figure 35: Fixture and load details

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Mesh information

Mesh type	Solid Mesh
Mesher Used:	Blended curvature-based mesh
Jacobian points for High quality mesh	16 Points
Maximum element size	0.0204289 m
Minimum element size	0.00102144 m
Mesh Quality	High
Remesh failed parts independently	Off

Figure 36: Mesh information

Study Results

Von Mises Stress

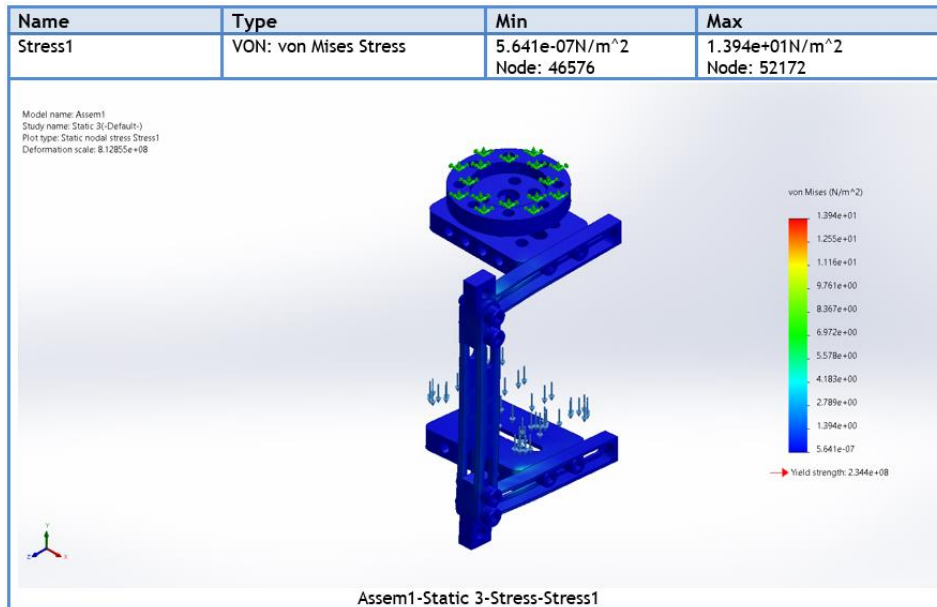


Figure 37: von Mises Stress study result

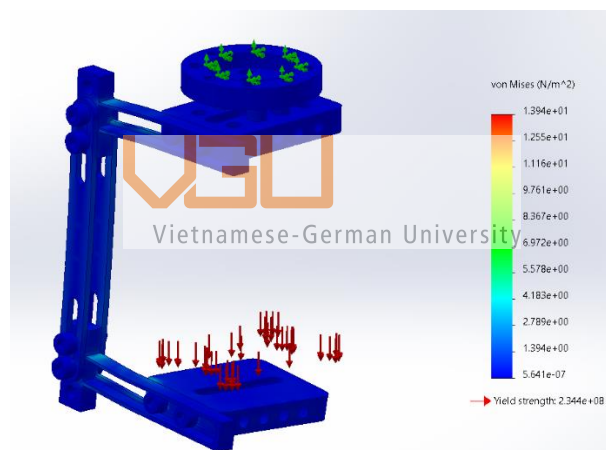


Figure 38: von Mises Stress study result another view

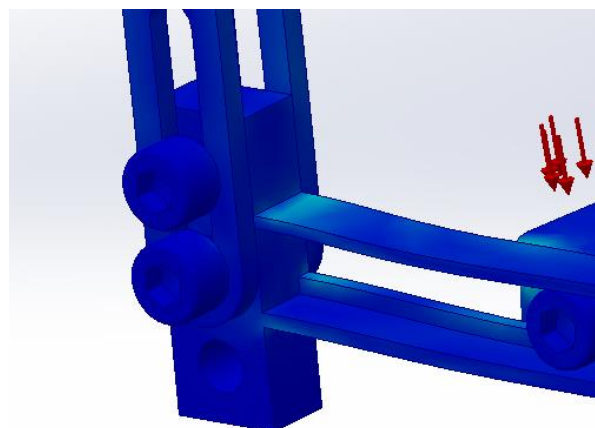


Figure 39: von Mises maximum stress location

Displacement

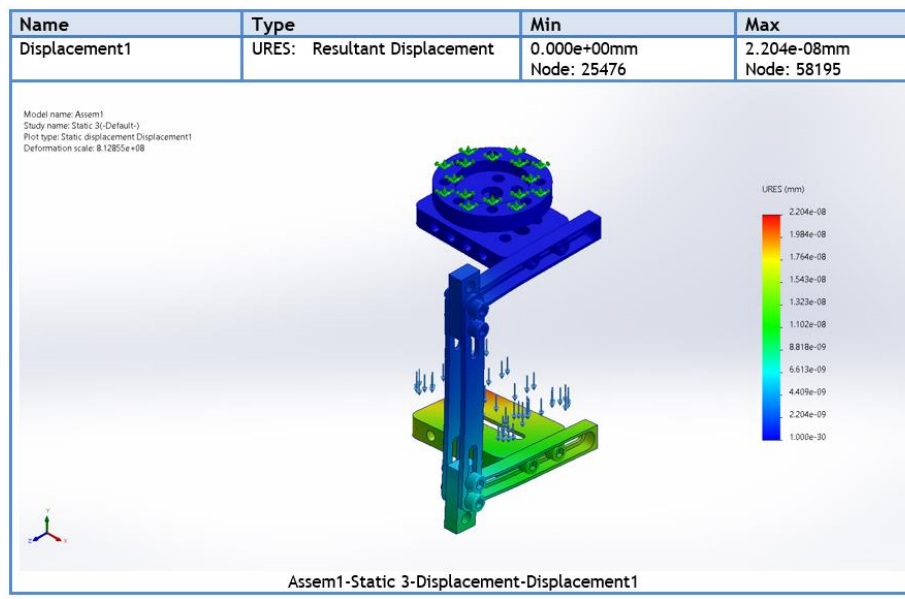


Figure 40: Displacement study result

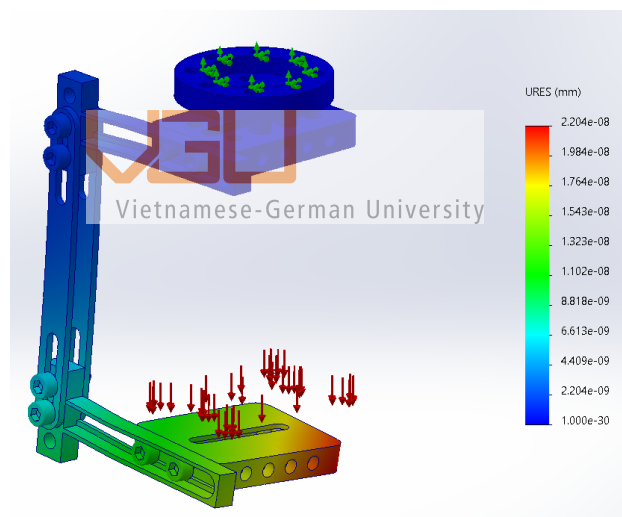


Figure 41: Displacement study result other view



Figure 42: Maximum displacement location

Conclusion

Although displacement and von Mises stress appear to have little impact on the structure while holding the camera, dynamic forces that arise when the robot moves the entire system haven't been considered in the FEM analysis. As a result, forces will behave differently when the base frame is moved in this scenario. Horse-shoe mount is added to the top plate to address this issue without using more complex FEM analysis on dynamic forces. The built-in horse-shoe on top of the camera will link to this mount, locking the entire camera in place with a second screw fastening between the horse-shoe mount and the upper plate. The forces won't have to go as far along the rig rod, all the way to the baseplate, thanks to this arrangement, which will give them alternative path from the robot flange to the camera.

Horse shoe mount



Figure 43: Horse-shoe connector



Figure 44: Horse shoe attached to the camera

3.6 Robot movement control

3.6.1 Path programming

Robotstudio, an ABB piece of software used to control and simulate stations with at least one robot and one robot controller, will be the only tool used to create paths and manage the focus system. The software features a simple programming language with basic operations like if, while, for... that is comparable to C++. This program will be quite user-friendly for those with coding knowledge. Wizard is a straightforward coding platform that the OmniCore controller supports for users who are not programmers (ABB, 2020). This type of coding allows the user to construct their program by selecting chunks of commands that are explained in a way that is accessible to beginners. This will be converted into commands by the Wizard and displayed in the program editors.

The major goal of this program, which is used for the project's testing phase, is to enable the robot to travel to various angles at a relatively modest speed. It also controls the analog signal, which coordinates the focus system and keeps the main item in focus. Running this program requires two primary commands:



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MoveL:

- Example code: `MoveL Location1, v150, z10, tool0;`
- Location1: the first expression of this function is a data of location, called robtargt. This data contains x, y, z coordinate of the tool and its rotation, as well as the robot configuration, also known as the robot's posture.
- V150: this is the speed data; this will command the robot to move with the speed of 150mm/s
- Z10: this is zone data, the zone is a sphere with the diameter given behind the letter "Z", in this case 10mm, around the point of destination. When the robot's tool has entered this zone, the pointer in the program will move to the next command and execute it. With this effect, the robot may not get exactly to the destination point but continue to move to the next destination if there are other Move commands under this line. This will create a smooth path for the robot.

SetAO

- Example code: SetAO AO1,5;
- The command will trigger an analog signal of 5V as an output through the DSQC1032.

WaitTime

- Example code: WaitTime 1;
- The pointer will stay at the command for 1 second before continuing

Accset

- Example code: AccSet 60 75;
- This will reduce the acceleration of the robot by 60% and reduce the time for this robot to reach this 60% acceleration to 75%. This command will smoothen the path of the robot, thusly remove unwanted judders.

For the first phase of this project, the robot will move to a point of destination, after that, the analog signal is set to change the focus of the camera. This first phase will mainly focus on the stability test of the system as well as the repeatability of the focus system to successfully set the focal length in time and on point. Here is the code of the path programming:



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```

PROC main()
  !Set acceleration percentage
  AccSet 60,60;
  !Set focus system by changing analog signal to 3V
  SetAO FocalSystem_BOARD_1_A01,3;
  !Wait at that position for 1s
  WaitTime 1;
  !Move exactly to Location62 with speed 150mm/s and default tool
  MoveL Location62,v150,fine,tool0;
  SetAO FocalSystem_BOARD_1_A01,4;
  WaitTime 1;

  MoveL Location2,v100,fine,tool0;
  SetAO FocalSystem_BOARD_1_A01,2;
  WaitTime 1;

  MoveL Location1,v150,fine,tool0;
  WaitTime 1;
  SetAO FocalSystem_BOARD_1_A01,6;
  WaitTime 1;
  MoveL Location22,v150,fine,tool0;
  WaitTime 1;
ENDPROC

```



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 Figure 45: Robotstudio path programming

3.6.2 Focus control programming

By using IDE from Arduino, the program that maps analog signals to PWM is shown below.

```

servo object to control a servo
pin used to connect the potentiometer
read the value from the analog pin

taches the servo on pin 9 to the servo objec

, 270);
// reads the value of the potent
// scale it to use it with the s
// sets the servo position accor
// waits for the servo to get th

```

Figure 46: Arduino UNO program

Chapter 4 Experiment/evaluation

4.1 Stabilization test



The stabilization clip is included in the appendix. The camera's auto-focus mechanism was used in this test rather than the focal system. This test demonstrates how inadequate the autofocus is. After a lengthy period of time, the autofocus can finally bring some details into focus, but once the robot has moved on to the next position, the system is unable to keep up.

The video wasn't sufficiently stable for filming. Judders typically occurred when the camera came to a complete halt or when the robot's movement abruptly changed direction. The issue was that the robot's base wasn't secure enough for it. Although the robot can accurately reach the intended location, this base was used for an exhibition with pick-and-place applications. This is adequate for picking and placing, but it is insufficient for cinematography, where stabilization is essential. The casing of the camera seemed to not be the source of judder, by simply fixing the base of the robot, the judders will be reduced.

4.2 Repeatability test

The repeatability of the focus mechanism is the primary objective of this repeatability test. The test is carried out in the manner described below: the robot will go to three distinct locations

with various distances between the lens and the main subjects in the frame, after which the analog signal is activated and the focus ring is rotated. These analog signals were pre-set, i.e., the robot was moved to each point along the specified path, and then the appropriate analog output was selected until the object came into focus.

The test revealed some noticeable frames with out-of-focus objects, which can be attributed to the lens' focus ring's design. The change in focal length will not be the same when the focus ring is rotated at various speeds. This might be a characteristic of this particular lens or it might be a norm for lens focus rings. The pace at which the analog signal changes when used to pre-set the focus system (from the Flexpendant) is different from the speed at which it changes when used in running mode. The speed at which the analog signal changes can be altered by including a function that progressively increases the analog signal and adding a WaitTime command in a loop. Here is a sample for this function, where the increment is calculated as a change between the wanted analog output value and the current value, all divided by 10. The waiting time before the next increment is 0.01s. This function will replace all the SetAO commands.

```
PROC focal_change(num x)
  VAR num y;
  VAR num z;
  y:= (FocalSystem_BOARD_1_A01 - x)/10;
  z:=FocalSystem_BOARD_1_A01;
  WHILE FocalSystem_BOARD_1_A01 < x DO
    z:=z+y;
    SetAO FocalSystem_BOARD_1_A01,z;
    WaitTime 0.01;
  ENDWHILE
ENDPROC
```

Figure 47: Gradual focal-system-change function

Chapter 5 Final discussion

This system's hardware is currently adequate. The housing didn't judder, and the focus system can turn the focal ring well. It is possible to 3D print replacement gears to make this design compatible with other digital cameras. If the focal ring diameter varies just slightly from the YongNuo 50mm, the driving gear's gear teeth can be left untouched while the gear's inner diameter is changed, maintaining the gear ratio. However, a new gear ratio needs to be determined if the lens's angle range changes.

To fix all of the system's flaws and refine the algorithm, further testing needs to be done. Currently, the path program primarily functions in a way that the focus system will begin the focusing process once the robot has arrived at the destination points. The focus mechanism may be able to operate in parallel with the movements of the robot with more study and development. Additionally, the control system can be simplified by integrating an Xbox controller into the program to control the robot's mobility. Basic functions like saving locations and switching between linear and orient movements can be implemented on the controller's buttons.... The project would be prepared to conduct field tests once these tasks were completed.



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The initiative will be the first step toward integrating robotics into the fields of computer vision and cinematography, which were previously uncommon, particularly in Vietnam. Additionally, because robots will perform the majority of the world's labor in the future, it will inspire more students, researchers, and video enthusiasts to learn more about them.

Chapter 6 Conclusions

As the filming industry continues to develop, many companies are looking for creative and innovative ways to compose videos and clips which integrate sophisticated camera angles or motions. On the other hand, a new field of computer vision has been developed for the past decades mainly focuses on reconstructing 3D model using sets of 2D images. The main scope of this paper is to design a camera mount that can be used with most common digital cameras on the market and a focus system that can control the cameras' focal length through the robot controller's program so that it can also be controlled in only one program.

Small brands and businesses are rising in number and they are in desperate need of enhancing their advertisement quality through short videos. A new field of computer vision focuses on generating 3D model using many 2D images and construct them together and with state-of-the-art technologies, good quality cannot be achieved. The project is to design a camera mounting system that can attach any common DSLR cameras to the robot arm and a focus system that can help to control the focal length of the camera through the same software that controls and designs the robot paths. The robot-camera project can give many businesses, students and researchers more opportunities to reduce cost, create better quality videos or expanding their work in a creative way.

The design must be organized in order to finish in a short period of time, and all the calculation must be considered before purchasing any components, keeping them in a minimum. This system's parts must be exchangeable to increase sustainability and they must also don't have sharp edges as well as the robot must have safety features to keep the user and the robot safe. All of these constraints are analyzed and present in an engineering language in the requirements list, while all the necessary tasks are planned in a timely order using Gantt chart. The estimated cost of the project is roughly 7 million VND. To grasp an overall view of the functions of the robot, and how each component works with one another, the function structure diagram is used.

On the current market there are supporting devices that allow users to hold and move the camera with smoother motion/reducing all the jitter movements made from users' body. Although these devices have been widely used in the market, there are still human-factors

taken into account, thus it is still very hard to have repeatability when shooting videos. All of these disadvantages can be filled with robot camera, because repeatability, stability, versatility and high-speed movements are fundamental aspects of a robot arm. Short Video

Advertisement, a project made a group of students that focuses on developing an algorithm which recommends all the camera position, angles and movements to users in order to have a great commercial video. However, the research only utilize smartphone as a recording device, with the phone is gripped by the robot's gripper, which cuts out users that use other video shooting devices e.g., DSLR camera, mirrorless camera... Motorized precision is one of first companies to share this idea and bring it to the world. They have robot cameras with different sizes for sale or rent. While Motorized Precision are looking for big companies, this project mainly aims at small businesses and students

After taking each aspect of all three robots into accounts, the GOFA seems to be the most suitable option for being mounted and operated with the camera system due to its overall ease of use, ease of operation, flexibility, and its structure is efficiently compatible with videography application. Handling capacity of the robot is 5kg, which is just enough for the camera system, even with additional weight for some light-weight lights and microphones. Out of the three it can be seen the GOFA has a slight advantage of reach. By having this robot structure, singularity positions can be avoided by having an offset where the 5th axis is bend 90°. Another reason why GOFA is suitable is because it runs on 220V AC, which is the common household power supply in Vietnam. Having a lightweight robot on studio will be beneficial because the it can be moved around easily to design new camera paths, shooting new angles. While having the ability to move around easily, CRB 15000 also installed with an easy programming wizard.

Nikon D5200 is the chosen camera for this design process due to its low-level in autofocus feature so that the project could support it and other low-level cameras. The chosen lens for this project is YongNuo 50mm f/1.8 lens with overall dimension of the focal ring is 73mm in diameter and 10.8 in thickness and an angle range of the focal ring of 140°

To control the focal length of the camera, which is located on the camera lens, a gear is used to wrap around the mechanism that is normally used on the lens to manually control the focus. From that a motor which can rotate to any desired angle commanded by Robotstudio will be in charge. Comparing the two suggests that Hiwonder LD-27MG is more compatible with what

the project is looking for, mainly because of the metal gear box. With a gear ratio of 0.518, the driving gear will have 53 teeth while the driven gear on the lens will have 101 teeth. To make this gear transmission flexible for all camera lens where each focal ring can be located uniquely, the sliding mechanism parallel to the axis of the lens is utilized.

Turning analog signal from the IO device to PWM for the servo is the purpose of the focus control system. Arduino UNO with the ATmega328P chip is chosen due to its specification and well-organized documents with large fan base with many resources. IO device of this system is ABB's Scalable IO with a base digital device and an analog add-on. The RC servo will connect to the 9th digital pin, this pin in the datasheet mentions it will output PWM signal. For the IO device, Analog output 1 from the IO device will connect to A0 pin of the Arduino UNO.

Camera case is consisted of 4 rods that are structured in a way to support the camera and the focus system stably on the robot without hindering the motion of the focus system, being too heavy and should be painted in black. The upper and lower plates have their responsibility to connect the camera to the mounting system and hold the camera steady in place. It is important that these plates follow the standards from the robot and the camera equipment. The entire system's material for manufacturing is stainless steel. After FEM analysis to reduce the stress and displacement, a horse-shoe mount is added on the top plate. This set up is expected to simplify the force line, giving it a direct path between the robot flange to the camera, without having to go along the rig_rog, all the way to the baseplate.

The path program is used for the testing phase of the project, the main purpose of the code is to allow the robot to move to different angles in a relatively slow speed, adding with controlling the analog signal to control the focus system so that the main object remains in focus. This first phase will mainly focus on the stability test of the system as well as the repeatability of the focus system to successfully set the focal length in time and on point. While in the focus control program, 5V of the analog input is divided into 1024 sections and each section is then map to 0° to 270°.

Through the stabilization test, the judders happened in this test was due to the unstable base of the robot, by simply having the base fixed, this problem will be reduced. On the repeatability test, noticeable frames during the test where the objects weren't in focus can be explained due

to the nature of the focus ring of the lens. When rotating the focus ring with different speed, the change of focal length will not be the same. By adding a function which gradually increase the analog signal and having a WaitTime in a loop, the signal changing speed can be modified.

Hardware performance is sufficient, but software performance will need more tests to improve the programming. Other functions like simplified control and parallel working between robot's movement and focal system could be added for the project to be ready for field tests.



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Appendices

Stability test video:

https://drive.google.com/file/d/1XS69vHNXxX1YGuCnVzK6kA2qnf0hCoAZ/view?usp=share_link

Repeatability test video:

https://drive.google.com/file/d/1OwRmQFn5pHIVMbYrmIIxVTN2oaYDiRiN/view?usp=share_link

Footages and photos of final hardware:

https://drive.google.com/drive/folders/1apxUWYYowogx2mnmNPSakFe654TmaiZb?usp=share_link



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