TRIBHUVAN UNIVERSITY

INSTITUTE OF ENGINEERING

PULCHOWK CAMPUS

A

PROJECT PROPOSAL

ON

4 DEGREE OF FREEDOM

MANUALLY CONTROLLED ROBOTIC ARM

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December, 2023

Acknowledgments

We extend our heartfelt gratitude to the Department of Electronics and Computer Engineering, Pulchowk Campus, for providing us with an opportunity to complete a minor project as fulfilment of curriculum requirements and submission of this proposal is in the same regard. We would like to express our sincere appreciation to Asst. Prof. Santosh Giri and Asst. Prof. Bibha Sthapit, Project Management Team of the Department of Electronics and Computer Engineering, for their guidance and encouragement throughout the preparation of this proposal. Our sincere thanks also go to the faculty members of the department, who have imparted their knowledge and expertise, laying the foundation for our project endeavors, most notably Assoc. Prof. Anand Kumar Sah. We are grateful for the conducive academic environment and the resources made available to us. Furthermore, we would like to acknowledge the collaborative spirit and intellectual exchange that the department and campus fraternity cultivates among its students. We are ecstatic to have an opportunity to translate curriculum learning to date into a project and cordially thank the Department of Electronics and Computer Engineering, and we are committed in fulfilling the academic and research aspirations that we have embarked upon.

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List of Abbreviations

ROS	Robot Operating System
DoF	Degrees of Freedom
D-H	Denavit-Hartenberg
ARM	Advanced RISC Machine
ADC	Analog to Digital Converter
DAC	Digital to Analog Converter
USART	Universal Synchronous Asynchronous Receiver Transmitter
SPI	Serial Peripheral Interface
I2C	Inter-Integrated Circuit
USB	Universal Serial Bus
OTG	On-The-Go
SDIO	Secure Digital Input Output
CPU	Central Processing Unit
FPU	Floating Point Unit
RTC	Real Time Clock
MEMS	Micro-Electromechanical Systems
IDE	Integrated Development Environment
PWM	Pulse width modulation
PC	Personal Computer
HCI	Human Computer Interaction

Abstract

Human Computer Interaction (HCI) has been a cornerstone in robotics and has garnered a lot of application in recent times. This project proposal explores the implementation a 4-DoF Manually Controlled Robotic Arm using input from a computer peripheral designed for versatility in applications such as assistance for the elderly, hazardous environment handling, and industrial process simulation. The arm employs servo motors controlled by an STM32 microcontroller, with input derived from a computer mouse for intuitive manipulation.

Keywords: arm, microcontroller, STM32, servo, motors, actuator, end terminus, IDE, Degrees of Freedom, forward kinematics, inverse kinematics, revolute coordinates

1. Introduction

1.1 Background:

A robotic arm is a type of mechanical arm, usually programmable, with similar functions to a human arm; the arm may be the sum total of the mechanism or may be part of a more complex robot. The links of such a manipulator are connected by joints allowing either rotational motion (such as in an articulated robot) or translational (linear) displacement. A robotic arm is a chain of links actuated by motors in joints. Human beings require a multitude of applications in which robotic arms are widely used, with purposes depending upon specific applications. A robotic arm is represented by a set of bodies connected in a chain by joints. Robotic arms are devised upon two broad factions being automated and manual approaches. End user has a better control over the functioning in manual controlled robotic arms. It requires in depth understanding of issues governing manoeuvre of the arm joints using an analog input source, along with the gripping mechanism.
Kinematic analysis is one of the first steps in the design of a robotic arm. It facilitates us to obtain information on the position of each component within the mechanical system. image courtesy RobotShop community.

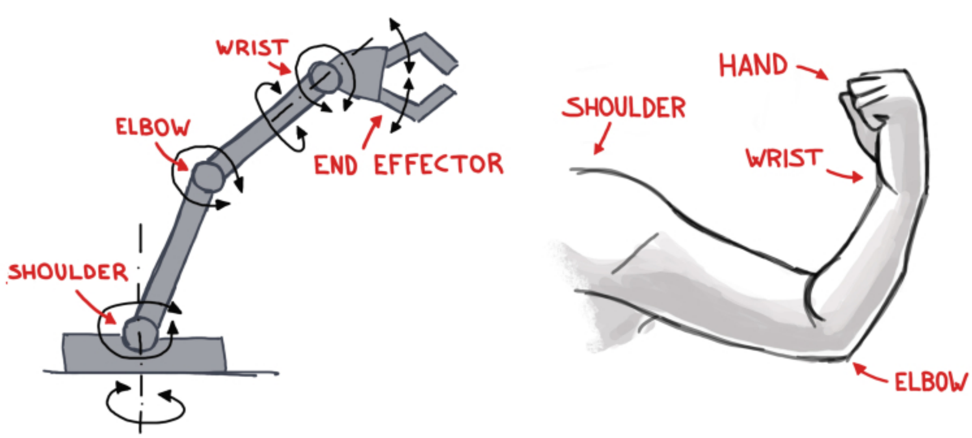

Figure 1.1: Mechanical similarties between robotic arm and human arm

Degrees of Freedom(DoF) are the allowed and represented number of motions of an object in predefined medium or space, both 2 dimensional and 3 dimensional. DoF is essentially the number of variables that represent possible motions of objects or assembly of objects. For realizing a 3-dimensional movement in space, pitch, yaw and roll are the three dimensions of movement. They serve to adjust the independent motions allowed to an object when it travels through a medium. DoF are chiefly divided to translational DoF and rotational DoF. Translational motion simply refers to a linear non-rotational motion. The scope of our project deals predominantly with the domain of rotational DoF. For an unconstrained, rigid object in 3 dimensional space capable of movement and rotation about any axis, 6 total DoF are possible: 3 translational DoF being along the 3 rotational DoF being about the three axes respectively.

- x axis: translational movement-surge and rotational movement-roll.
- y axis: translational movement-sway and rotational movement-pitch.
- z-axis: translational movement-heave and rotational movement-yaw

- **Shoulder Joint** Most prominent and highest load bearing joint in the arm. Performs pitch, yaw and roll.
- **Elbow Joint** Provides extension and retraction. Performs pitch.
- **Wrist Joint** Provides end effector terminus to be manoeuvred in 3-dimensional space. Performs pitch, yaw and roll
- **Hand** End effector terminus

The kinematic model defines the relationship between each link and joint of the robot mechanism. This definition is thereafter fed into the actuators for realizing necessary coordinates as terminal positions. The kinematic modeling is realized with 2 subsections; Forward and Inverse. The forward kinematics consists of finding the coordinates of the terminal actuator in the space feeding into the input, the movements of its joints and joint angles, while the inverse kinematics consists of the determination of the joint variables corresponding to a given terminal actuator position and orientation within the work envelope. Work envelope is the area in free space which the robotic arm can access. A 4 DoF robotic arm consists of a waist, shoulder, elbow and wrist as its geometric configuration and the rotational movement of these component defines the position of the end effector terminus. It involves the application of both forward and inverse kinematics.

1.2 Problem statements

Elderly people and specially able people need mechanical support for commute of objects in their day to day activities for which they are directly dependent on other people. Moreover, in areas of improper sanitation and bio-hazard where direct manual contact and intervention are risk-prone, a robotic arm is the solution.

1.3 Objectives:

- To recognize an analog input from the user for picking up an object and placing it.
- To apply inverse dynamics for control of various degrees of freedom in a single compound body.
- To develop the understanding and apply the comprehension of Robot Operating System(ROS) for control of a compound mechanical assembly.

1.4 Scope

- **In home environments** Example being: A robotic arm installed in the wheelchair to help the disabled persons grab things on the floor, feed, and drink, open and close the fridge and grab things inside and do the physical tasks otherwise daunting.
- **Performing tasks in dangerous environments** which still require a level of manual intervention like bomb disarmament and disposal.
- **Simulating industrial and manufacturing applications** in automating execution of repetitive and manually exhausting tasks in industrial assembly lines.
- **As surgical end effectors.**

2. Literature Review

The advent of present day Robotic Arms began with the proliferation of electronics and incorporation of microelectronic circuits in juvenile arm-emulating gadgetry of that time, circa late 1950s. However, they drew inspiration from da Vinci's scholarly notebooks on mechanically simulating human motion and attributes. His design comprised of a front wheel driving rack-and-pinion architecture, documented at around December 1478 incorporated heavy anatomical inspiration from human musculo-skeletal anatomy.

2.1 Related work

The first "position controlling apparatus" was patented in 1938 by Willard Pollard, eventually issued on 1942. This was a spray finishing robotic arm that had five degrees-of-freedom and an electrical control system, which was realized into manufacturing later by Harold A. Roselund(1944). Unimate introduced its first robotic arm in 1962. The "Rancho Arm" was a major breakthrough in emulation of flexibility similar to that of a human arm. Originally designed for the handicapped, it became one of the first arms to be controlled by computer when the project moved to Stanford in 1963 [5]. This marked the commencement of use of microelectronic components in robotic arms. Hereafter, micro-controllers are predominantly the central component of the robotic arms, which are highly streamlined. Along with proliferation of industrial and assistive robots, many scholarly research along with open source projects facilitating simulation of robotic arms in multiple DoF are conveniently available, with a micro-controller based realization being the common denominator.

This paved the way of integration of components to further facilitate integration of Human Computer Interaction conveniently. Peter Bajcsy et. al. [8] have proposed integration of human computer interface components like mouse and keyboard as a source of control signals for robotic actuators. The study has explored familiarity with computer components as an intuitive source for robotic control. Their study informs the design of input source of our project.

The findings from T. Arunkumar [9] shed light on challenges associated with mapping wireless mouse movements to robotic arm motions and suggest avenues for refining control strategies. Gesture Controlled robotic arm is another avenue which despite seeming rhetorically distant potentially provides us with useful methodologies to translate input from input sources to actual control signals for the motors in the microcontroller and the study from J. Islam et. al. [6] have provided valuable insights into our proposed methodology in this regard. Kruthika et. al. [2] have proposed a holistic robotic arm implementation using kinematic approach, quite similar to our aspirations. Their study has provided related implementation details.

2.2 Related theory

The control strategies for the robotic arm comprise of kinematics. Efficient kinematics modeling of robotic arm integrate both forward and inverse kinematics. K Asano [7] proposed pioneering methods and necessary mathematical formulations that provide perceptive suggestions for devising necessary algorithms for arm action and control. Furthermore, studies from Mohammed et. al. [4] contribute on planning paths based on the devised mathematical formulations of forward and inverse kinematics for robotic arm in revolute coordinates. Despite their domain having been predominantly GUI-based, it offers novel execution strategies based on kinematics modeling. The summary of collected mathematical formulations are represented herewith:

2.2.1 Forward kinematics:

For calculating the position of the end effector with respect to the given work envelope, we require forward kinematics. the set of joint link parameters is provided to the microcontroller and it calculates the position of the end effector through given parameters. Denavit-Hartenberg(D-H) parameters and successive screw displacements in the geometry are applied to realize forward kinematics. D-H parameters works using four parameters twist angle, link length, link offset and joint angle, represented by α_i, a_i, d_i and θ_i respectively.

$$\begin{bmatrix} C\theta_i & -S\theta_i\mathrm{C}\alpha_i & S\theta_i\mathrm{C}\alpha_i & \alpha_i\mathrm{C}\theta_i \\ S\theta_i & C\theta_i\mathrm{C}\alpha_i & -C\theta_i\mathrm{S}\alpha_i & \alpha_i\mathrm{S}\theta_i \\ 0 & S\theta_i & C\theta_i & d\theta_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Equations (1):

$$\mathrm{Si} = \sin i, \quad \mathrm{Ci} = \cos i \tag{2.1}$$

$$\mathrm{Si} = \sin i, \quad \mathrm{Ci} = \cos i \tag{2.2}$$

Equation (2):

$$nT_0 = 1T_0(q_1)2T_0(q_2)\ldots nT_{n-1}(q_n) \tag{2.3}$$

Overall transformation matrix:

$$T = \begin{bmatrix} C_1S_aC_5 - C_1S_aS_5 + S_1C_5 & C_1C_a & C_1 & c \\ S_1C_bC_5 - C_1S_5 & -S_1S_bS_5 - C_1C_5 & S_1 & c \\ -C_bC_5 & C_bS_5 - S_b & -S_b & d \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.4}$$

Where:

$$C_{23} = S_{23} = a$$
$$C_{234} = S_{234} = b$$
$$L_2C + L_3C_a + L_5C_{234} = c$$
$$L_1 - L_2S_2 - L_3S_a - L_5S_b = d$$

2.2.2 Inverse kinematics:

Inverse Kinematics is the procedure in which the joints are controlled in order to achieve the end position, given the position and orientation of the robotic arm. Solving Inverse kinematics is important compared to forward kinematics, as it can move the gripper to the target position, which would be helpful in grasping any object at the target location, such are the suggestions from the study by Cheng et. al. [1]. Algebraic analytical methods result in complicated solution as the Degree of Freedom (DOF) increases. The target location is manually entered, algorithm checks whether the target is within the workspace, if the target object is within the location, Jacobian matrix is calculated and pseudo inverse is also calculated.

Given a robot with end-effector coordinates (x, y, z) and joint variables $\theta_1, \theta_2, \ldots, \theta_n$, the Jacobian matrix is calculated as follows:

$$J = \begin{bmatrix} \frac{\partial x}{\partial \theta_1} & \frac{\partial x}{\partial \theta_2} & \cdots & \frac{\partial x}{\partial \theta_n} \\ \frac{\partial y}{\partial \theta_1} & \frac{\partial y}{\partial \theta_2} & \cdots & \frac{\partial y}{\partial \theta_n} \\ \frac{\partial z}{\partial \theta_1} & \frac{\partial z}{\partial \theta_2} & \cdots & \frac{\partial z}{\partial \theta_n} \end{bmatrix} \tag{2.5}$$

The pseudo-inverse of the Jacobian matrix, denoted as J^+, can be calculated using the Moore-Penrose pseudoinverse:

$$J^+ = J^T(JJ^T)^{-1} \tag{2.6}$$

References from [4]

3. Proposed Methodology

The proposed methodology for the development of the robotic arm involves a systematic integration of the four essential components: control signals generator, mechanical body structure, actuators and electrical connector components. The core control signals generator consists of a microcontroller and corresponding program development environment in a PC. Actuators setup comprises of servo motors positioned to ensure optimal control upon the centre of gravity, thereby providing the necessary stability. The mechanical body structure is designed for durability and flexibility, taking into account the range of motion required for the 4 DoF. This structure is to be engineered with lightweight yet sturdy materials to balance strength and agility, therefore the prominent alternatives become customized Aluminium frames or 3D printed frames. The electrical cables facilitate communication between the control unit and the various components of the robotic arm. Special attention is to be given to cable management to prevent interference with the arm's movements. The proposed methodology emphasizes a holistic approach, addressing not only individual component design and functionality but also their cohesive integration to achieve an efficient robotic system. Through rigorous testing and iterative refinement, the methodology aims to yield a 4-DoF robotic arm that excels in precision, reliability, and ease of control through mouse input, thereby fulfilling the project's overarching objectives.

3.1 Feasibility Study and Requirements

The feasibility of the project in entirety consists of individual study of various project components, which act cohesively to achieve the completion of the project. The most important areas of feasibility requirement are the following:

3.1.1 Mechanical Components:

The robotic arm will require mechanical components in arm structure itself and a mount to support the load capacity of the arm. Aluminium Frames or 3D printed solutions are fairly feasible.

3.1.2 Electrical Systems:

The electrical systems of the robotic arm include the power supply and connection systems. A reliable power supply capable of providing sufficient power for the motors and control systems can be arranged from rechargeable Li-ion batteries of necessary wattage. Careful wiring to avoid short circuits and interference in the arm movement is paramount.

3.1.3 Software Programming

The software programming is perhaps the most demanding facet of the project. The software requires a high-level programming language in C/C++, and will require a deep understanding of robotics and control systems. The proposed microcontroller STM32 has its proprietary IDE which provides support for both the aforementioned alternatives.

3.1.4 Testing and Quality Assurance

Once the robotic arm is assembled, it will need to be thoroughly tested to ensure that it works as expected. This will involve testing of all the four chief components of the project. The site of project development must be spacious enough to incorporate the project apparatus along with supplementing logistics like multimeters, testers and power supplies.

3.2 Material Requirements:

The entire robotic arm is built on an aluminium chassis mounted upon a solid base.The following materials are the key components required for the assembly of the project:

3.2.1 STM32 Microcontroller:

The STM32 microcontroller is a family of 32-bit microcontrollers produced by STMicroelectronics. It is based on various ARM Cortex-M cores, which are designed to offer high performance, low power consumption, and real-time capabilities. The STM32 microcontroller has a wide range of features and peripherals, such as timers, ADCs, DACs, USARTs, SPIs, I2Cs, USB OTG, SDIO, and more.
The STM32 microcontroller's high performance, low power consumption, real-time capabilities, and wide range of features make it an excellent choice for the project.

3.2.2 Servo Motors:

This project makes use of the model 996R motors in order to handle the motion of the arm. The motors take input from the motor driver to drive the body of the arm as well control the action of the gripper module.

3.2.3 Servo Motor Driver:

The driver converts commands from the main controller into electrical signals and transmits the signal to the motors, producing motion proportional to the signal. In this project, the PCA9685 motor driver is chosen.
The PCA9685 motor driver is a device that can control up to 16 servo motors or 4 DC motors with only two pins on the microcontroller. It uses the I2C protocol to communicate with the main control chip, which can be an STM32, or any other compatible board.

3.2.4 Gripper Module:

An aluminium robotic gripper of compatible size and weight is to be used in the project.

3.2.5 Mouse:

In our project, the primary input is sourced from a computer mouse. The mouse's movements are processed by a computer system, which then relays this data to a micro-controller. The micro-controller translates these inputs into appropriate signals. These signals are then sent to a driver, which in turn controls the motor system to execute the desired actions. This process ensures the precise operation of our 4 Degree of Freedom Manually Controlled Robotic Arm.

3.3 Data Collection:

A comprehensive methodology is required for the systematic collection of data to assess the performance and usability of the robotic arm, focusing on key metrics such as accuracy and response time.

3.3.1 Defined Objectives:

The primary objective of this data collection is to assess the performance and utility of the robotic arm.

3.3.2 Variables:

Variables to be measured include positional accuracy according to the peripheral input and response time after the input upto the actual actuating. The delay and inaccuracies will be quantified to assess the overall performance of the robotic arm.

3.3.3 Data Collection Procedures:

Upon operating the robotic arm manually to perform specific tasks repetitively, the deviation from previous performance will be quantified. Data collection for this procedure will occur in a controlled environment to minimize external influences.

3.3.4 Documentation:

Any unexpected issues or modifications made during the data collection process will be documented for future reference. This documentation will be valuable for potential improvements in subsequent studies.

3.4 Potential Issues:

There are many potential issues and solutions that may be encountered while completing this project. The following are some of the most important ones:

3.4.1 Accuracy:

The accuracy of the robotic arm depends on the quality of the actuators and controllers. It may be necessary to calibrate them to ensure they work properly and give consistent results. It is also need to use feedback mechanisms such as encoders or potentiometers to measure the actual position and velocity of the joints and compare them with the desired values. If there is any discrepancy, the parameters or algorithms may need to be adjusted accordingly.

3.4.2 Stability:

The stability of the robotic arm depends on the balance between the forces acting on each joint. If one joint is overloaded or underpowered, it may cause instability or oscillations in the arm. It is necessary to design a robust controller that can sense and compensate for any disturbances or errors in the system.

3.4.3 Flexibility:

The flexibility of the robotic arm depends on the range of motion and articulation of each joint. If one joint is too stiff or too flexible, it may limit the performance or functionality of the arm. It is required to design a suitable kinematics model that can represent all possible configurations of the arm.

3.4.4 Safety:

The safety of the robotic arm depends on how well it can avoid collisions with other objects or people in its environment. It may be needed to implement emergency stop and limit switches to prevent any damages.

4. Proposed Experimental Setup

The experimental setup chiefly deals with the data and configuration collection for the robotic arm. Successive experiments and inferences derived from their completion will stipulate the mechanical design and the algorithms devised. The experimental setup involves the following setups in concoction:

4.1 Hardware Setup:

- A potentiometer is connected to the microcontroller input via a breadboard. The potentiometer will be rotated and servo motor movements according to the analog input will be noted in the serial monitor provided by the microcontroller IDE. A potentiometer has 360 degrees of movement, whereas the servo meter has 180 degrees of movement. Hence, the potentiometer input will roughly mapped to the movement of servo motor in the ratio of 2:1. Connection will be done in accordance to default potentiometer configuration

- A mouse will be connected via standard USB terminal of the personal computer. The analog input is mapped into by the microcontroller to its serial monitor.

- The comprehension about variation of servo movements according to the variation of potentiometer will now have mapped to the mouse input. The rotation of mouse about its axis will be linked to the servo that rotates the waist of the setup. Movement of the scroller will be linked to the servo at the elbow and the arm of the setup. The elbow and arm joints will move in sync to give the required position of the arm. The mouse left click will be linked to the gripper, each alternate click resulting in closing and opening of the gripper.

- The distances between the joints of the robotic arm will be determined by the mouse input sensitivity. Better the sensitivity, larger will be the servo action. It is simply the scaling of end spatial co-ordinates of the mouse input into the work envelop of the robotic arm.

- The positive and negative pins of the servo will be connected to VCC and GND of the microcontroller. The PWM PIN of the servo motor will be connected to an output pin of the microcontroller. The input provided by the mouse will be mapped to the servo motors in the respective positions. The rotation of the parts of the setup according to the movement of the servo motors are noted and calibrated likewise.

- Auxiliary hardware equipments like multimeter and testers are required to check the validity of electrical connections.

4.2 Software Setup:

Software support for microcontroller is provided by STM32 IDE, that supports high level languages C and C++. Both procedural and object oriented approaches are feasible, and the choice among these two will be done along the course of project development, taking into account multifarious factors like flexibility, ease of use and speed of compilation in the microcontroller.

The simulation for mouse control can be brought about by MATLAB or similar simulation development environment.

5. Proposed System design

We divide the overall system design into two parts namely hardware design and software design. The main controller for this system will be an STM32 microcontroller which will be connected to the mouse input through PC and run a control algorithm to control the actuator(servo motor). image courtesy [10]

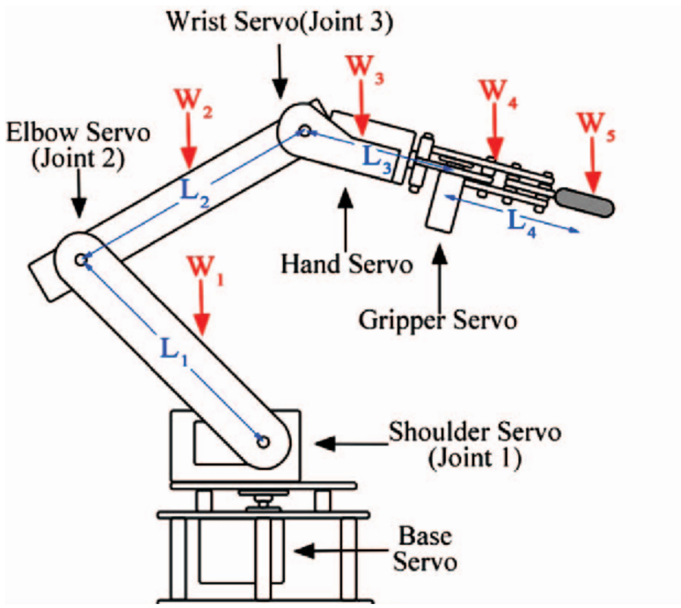

Figure 5.1: Proposed schematic

5.1 Hardware Design:

The system is a combination of servo motors, gripper and aluminium frame. Each servo motor accepts input through the motor driver, which in turn accepts input from the micro-controller. The input is taken via a computer mouse.

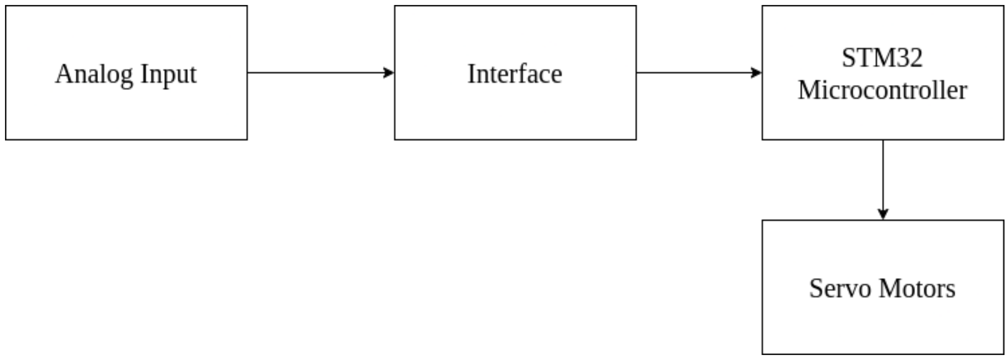

Figure 5.2: Hardware block

5.2 Software Design:

The approach applied for software design in our aspirations is spiral model. We have opted for this approach because in a hardware project, multiple iterations on a working prototype is required for robust functioning and to add features further. In the design of the robotic arm. the STM32 controller is employed to control the system. The input from the computer mouse is taken into the PC which maps the input to the STM32 IDE. The servo motors used in the robotic arm is controlled by the code implemented in STM32 IDE. Inverse and forward kinematics are employed to calculate the movement of servo motors.

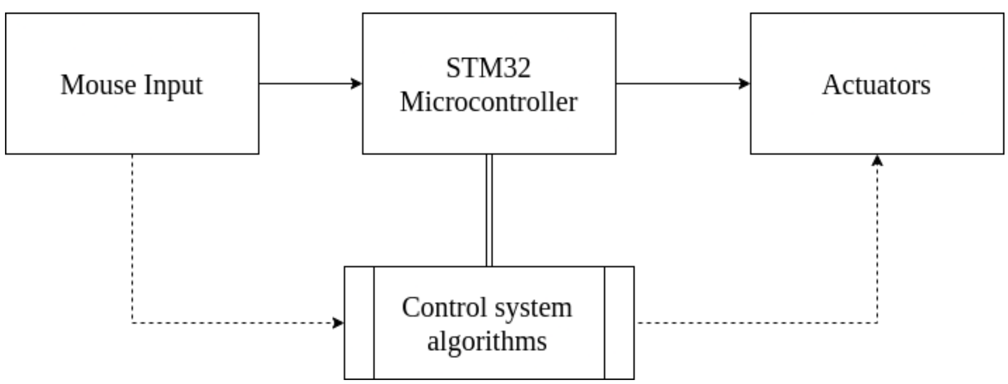

Figure 5.3: System block

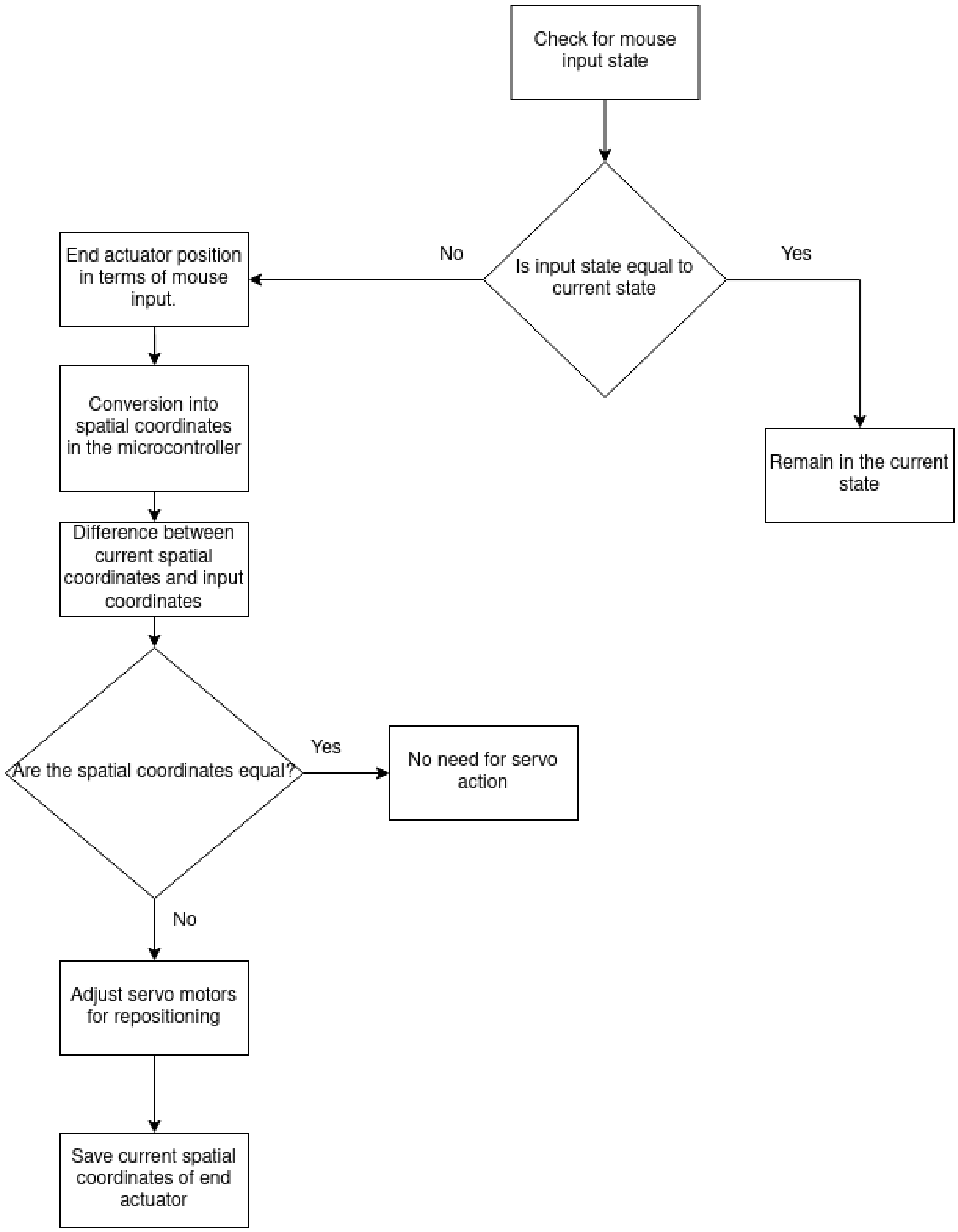

Figure 5.4: General system flowchart

6. Timeline

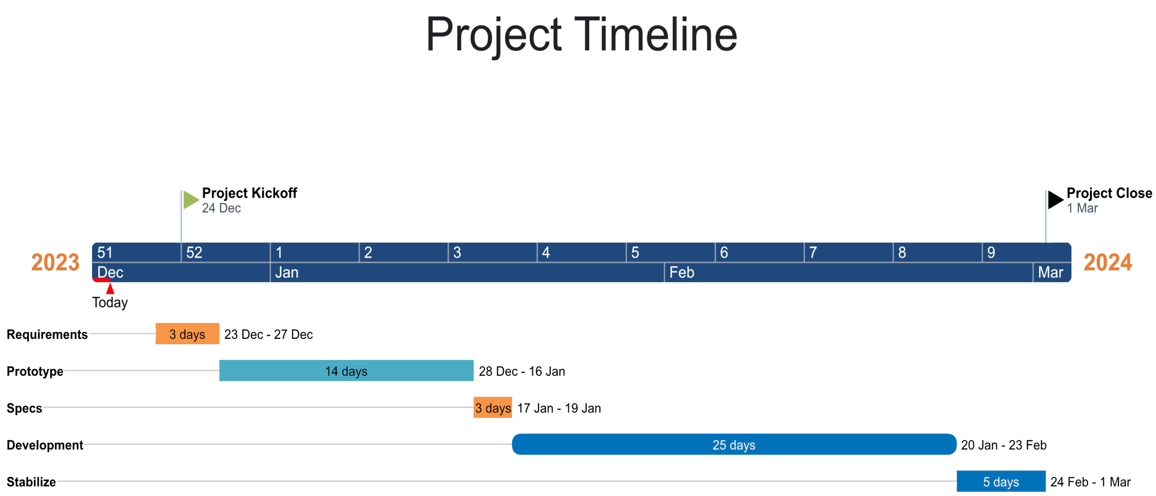

Figure 6.1: Project completion roadmap

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