Prototype and Simulation of a Single-Board Computer Actuator Arm for Applications in Assistive Patient Lifts

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Abstract*– Healthcare providers worldwide must adopt best practices to ensure patient safety and likewise their own safety. The utilization of a Patient lift assistive device is one such best practice used by most healthcare providers to mitigate the risks associated with both patient and provider injuries. In this research, the authors expand on the conceptual design of a patient lift by designing and analyzing a prototype actuator arm. The paper presents an overview of two critical components for actuator operations. Firstly, the functional operation of the actuator was developed using a DC motor, relays, sensors, and Python programming of a Single-Board Computer. Secondly, a compound spur gear box was designed and analyzed using Creo 3.0 Mechanism to simulate the kinematic behavior of the parametric model.

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I. INTRODUCTION

Safety is a fundamental component of patient care in health systems worldwide. In the case of Latin America, such as Uruguay, Mexico, Colombia, Argentina, and Spain, countries are working to show the importance of the use of devices for patient care in the state of rehabilitation. Moreover, hospital security and safety are of paramount importance for hospitalized patients. Reference [1] strongly recommends that standards should be set, for example, regarding conditions of safety of facilities and equipment, application of techniques and technologies, risk management, safe clinical practices, and other aspects.

Likewise, reference [2] discussed specific recommendations for nursing staff regarding the prevention of patient injury during hospitalization. These recommendations included programs to reduce the risk of injury of patients during hospitalization. According to the literature, 70% of the patients who have fallen had suffered some form of physical injury. In our opinion, this statistic represents a high percentage of injuries that warrants attention. Among the safety measures they presented in their research, the use of special attachments, such as walkers, lift, etc., are included as necessary to assist the patient in their mobilization or transfer.

Another factor to consider is the exposure of healthcare workers to increased injuries as a direct result of patient mobilization. In this order are works of [3], [4], and [5]. In most cases, it is stated that the main risks presented are physical, among which, special mention is made of the lack of protection of the spine, and ergonomic related injuries. The various research studies were in agreement, emphasizing the adoption of uncomfortable positions along with physical effort of healthcare providers during the transference and mobilization of patients and equipment has led to harmful ergonomic conditions resulting in musculoskeletal injuries.

Patients' recovery and rehabilitation were also explored in a number of research studies. Reference [6] indicated that the use of an orthopedic device was needed as an aid to patient movement. In continuing the bibliographic review in this same order, we found that in Colombia, reference [7] has developed an investigation for the creation of prototype equipment for patient rehabilitation. The project was developed under the concept of Rehabilitation Engineering with a high cost-benefit ratio. Finally, we mention the work of reference [8] who emphasized the use of assistive devices. The design characteristics of these devices must be considered particularly in applications for rehabilitation centers for people with motor disabilities.

In prior work, a Finite Element Analysis (FEA) of the conceptual design of a patient lift was conducted [9]. During the study, an FEA of the boom of the patient lift was conducted to determine design parameters for geometry thickness and material selection. As an extension to the initial study, this research paper focused primarily on the operation and functionality of the actuator arm. This was achieved by developing a prototype and conducting a simulation of two critical components required for the operation of the actuator arm. To achieve this, the paper presents an overview of (a) an electrical prototype and Python programming code development, and (b) the mechanical design and simulation of a compound spur gearbox train for increased torque performance.

II. ELECTRICAL CONTROL PROTOTYPE

The electrical functionality of the actuator operation consisted of verifying the motor movements of forward and reverse, operation of adjustable limit switches and

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development of the software code required for operational control. The prototype consisted of the following components, Raspberry Pi (Single-Board Computer, DC motor, Relays, Hall Effect sensors, pushbutton switches, resistors and a magnetic actuator.

A. *Prototype Hardware*

The Raspberry Pi 3 is a 1.2GHz Single-Board Computer that is driven by Broadcom’s 64bit ARMv7 Quad Core Processor. Fig. 1 (reference) highlights, 1GB RAM, on board Wi-Fi, 4 USB ports, full size HDMI, micro SD port, Ethernet connector, camera and audio ports, micro-USB power, and a 40 pin extended General Purpose Input Output (GPIO) connector [10]. The Raspberry Pi operates on the open source Linux operating system distribution called Raspbian.

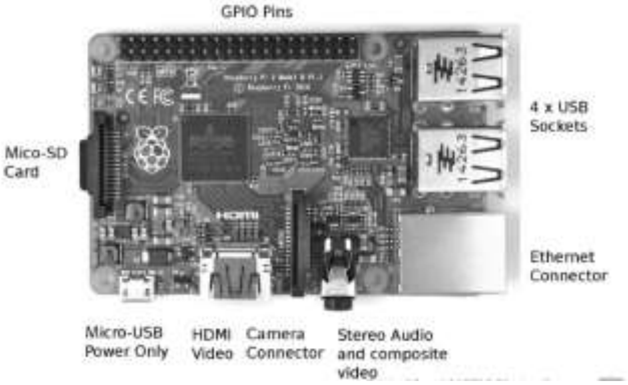

Fig. 1 Anatomy of Raspberry Pi 3

A 24V DC motor of nominal torque, power, and no load speeds of 5Nm, 16.8W, and 40rpm, respectively, was used to mimic the actuator arm motions. The angular velocity was calculated and simulated during the compound spur gear train design.

The relay selection consisted of a 5VDC 8-channel interface board of 15-20mA drive current per channel. The relay board was equipped with indicator LEDs and high current relays rated at AC250V @ 10A or DC30V @ 10A.

The Hall Effect sensors were a low sensitivity unipolar switch (Melexis US5881) used as a proximity detector for the actuator limits. The sensors had an operating voltage from 3.5 - 24VDC. The sensors measured a logical high when not sensing then dropped to a logical low during sensing (magnet present).

B. *Design and Operation*

The prototype design consisted of the following major functions:

- Motor direction to simulate the extension and retraction of the actuator stroke
- Hall Effect sensors to serve as adjustable upper and lower limit sensors
- Push button switches to operate the up and down motion of the actuator with indicator LEDs
- Python programming code to control the actuator arm

Direction for the DC motor was achieved by reversing the current direction (polarity) to the motor. This was accomplished through an H-Bridge circuit. As illustrated in fig. 2, the H-Bridge circuit design consisted of connecting the DC motor to four relays that were controlled by GPIO Pins 12 and 15. The pins were connected to alternate relays are shown in fig. 2. The motor power was supplied by an independent 24VDC power supply. Two push buttons are wired per the schematic to GPIO pins 11 and 13. Bias and current limiter resistors were included for proper operation of the push button switches. The Hall Effect sensors were biased with a 1kΩ resistor and sensed on GPIO pins 16 and 18. Since the relay board was equipped with status LEDs, the prototype did not require additional indicator LEDs for motor status and direction. The additional LED schematic circuit was provided for the connectivity of additional status LEDs if none are available with the relay selection. The circuit was designed for a 6mA current flow with a driving signal of 3.3V and a pull down resistor of 560Ω.

The following Python code was developed to control the operation of the actuator arm:

```
    import RPi.GPIO as GPIO
    import time
    GPIO.setwarnings(False)
    GPIO.setmode(GPIO.BOARD)
    GPIO.setup(12,GPIO.OUT)
    GPIO.setup(11,GPIO.IN)
    GPIO.setup(13,GPIO.IN)
    GPIO.setup(16,GPIO.IN)
    GPIO.setup(18,GPIO.IN)
    GPIO.output(12,1)
    GPIO.output(15,1)
while True:
    if GPIO.input(11)==1 and GPIO.input(16)==1:
        Time.sleep(.1)
        GPIO.output(12,0)
    elif GPIO.input(16)==0:
        GPIO.output(12,1)
    elif GPIO.input(13)==1 and GPIO.input(18)==1:
        Time.sleep(.1)
        GPIO.output(15,0)
    else:
        GPIO.output(12,1)
        GPIO.output(15,1)
GPIO.cleanup()
```

The operations of the actuator arm prototype consisted of control code developed in Python, and the hardware setup configuration as detailed earlier. Operational control was initiated by activating the forward push button switch. This supplied a logical high to the Raspberry Pi input GPIO pin 11.

This in turn, as defined in the code, starts the motor in the forward direction only when the extended Hall Effect limit sensor was also a logical high. If it is a logical low, this would mean that the actuator arm is already fully extended, therefore, cannot be extended further. With both the forward push button and extended Hall Effect sensor at a logical high, the motor will rotate causing the actuator arm to extend throughout its stroke. As the arm extends and the attached magnet moves within proximity of the extended Hall Effect sensor, the sensor reads a logical low, causing the motor and actuator arm to stop.

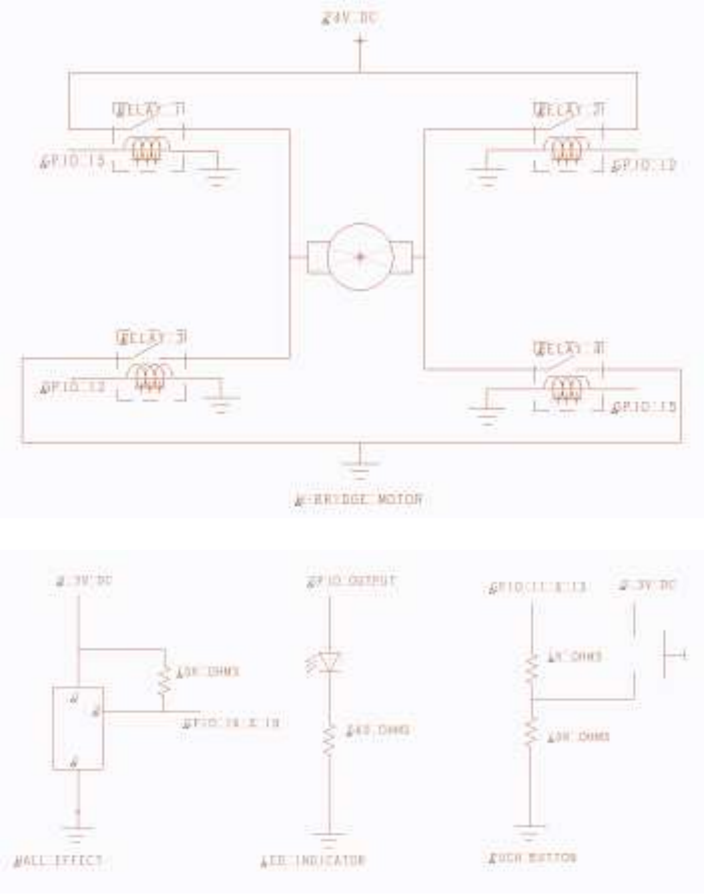

Fig. 2 Schematic of Circuits

For the retraction of the actuator arm, the reverse push button must be activated and the retracted Hall Effect limit sensor must not be at a logical low. A logical low would indicate that the actuator arm was fully retracted. Sensing of the sensors was recorded through the input GPIO pins 16 and 18. Motor direction, which provided the extension and retraction of the actuator arm was controlled by the Raspberry Pi GPIO pins 12 and 15. With all conditions satisfied, as explained earlier, output signals from GPIO pins 12 and 15 created current paths through two alternate relays (1 and 4 or 2 and 3) that changed the voltage polarity, therefore, changing the motor direction. Fig. 2 illustrates the two alternate relays being hard wired to GPIO output pins 12 and 15. This design ensured both relays were powered simultaneously, reducing the risk of signal lag. This also freed-up an additional two GPIO ports as compared to driving each relay separately.

Fig. 3 displays the physical connectivity of the prototype. As shown, the Raspberry Pi was connected to a breadboard through a 40 pin ribbon cable. The push button switches and Hall Effect sensors were located on the breadboard. The bread board was wired to the relay board where the 24VDC power and DC motor connectivity was completed through a second breadboard.

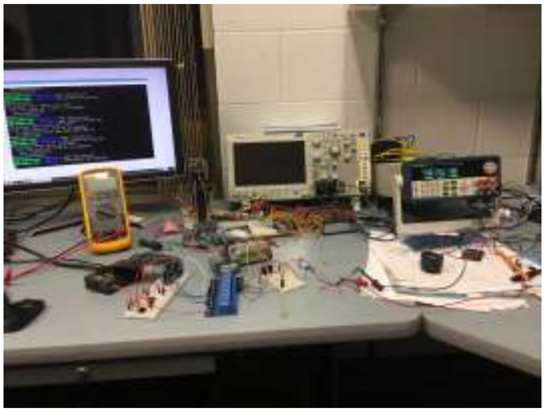

Fig. 3 Electrical prototype build

III. MECHANICAL DESIGN AND SIMULATION

Gear train selection was a critical component of the actuator arm design. Patient lift assistive devices must be quiet during operations and able to sustain the recommended load for patient safety. Although many motor manufacturers provide solutions for gearboxes, this section outlines the design and kinematic behavior of a compound spur gear train.

A. *Compound Spur Gear Train*

Due to the compact design of an actuator, DC motors are limited to certain form factors. As a result, the torque requirement of a DC motor will not be sufficient to satisfy the application requirements. However, this can be overcome by coupling a gearbox mechanism to the motor. A gearbox reduction ratio will reduce the speed of the motor but increase the torque. Since patient lift applications are not highly dependent, for the most part, on speed which can introduce instability in the system, a gearbox reduction mechanism is ideal for reducing speed but increasing output torque.

A compound spur gear train can be used for high gear reduction ratios. The gear train consists of two or more gear pairs. The motor is connected to the driving gear, which in turn drives the driven gear. The gear ratio can be calculated as the product of all the individual pairs of gears. The compound spur gear train depicted in fig. 4, for example, has two gear pairs. The following equation can be used to calculate the resultant gear ratio.

$$g_r = \frac{d_{p1}}{d_{g1}} \cdot \frac{d_{p2}}{d_{g2}} \quad (1)$$

Where: d_{p1}, d_{g1}, d_{p2}, d_{g2} = pitch diameters of the pinion and gear pairs.

From fig. 4, let us assume the two gear pairs have pitch diameters of 50, 120 and 60, 125. Therefore, using (1), the gear ratio calculation would be (50/120) X (60/125) = 1/5. The gear ratio of 1/5 means that while the angular velocity is reduced 5 times, the output torque which is inversely proposal to the angular velocity will increase 5 times assuming zero loss to friction [11].

Fig. 4 Compound Spur Gear Train

The following kinematic parameters were set in Creo Mechanism 3.0 fig.5. With the gears defined and the servo attached to the driving gear, the start time, end time, frame rate, minimum interval, and initial configuration were set to 0, 1, 100, 0.01, and current, respectively. The resultant angular velocity calculated from an input angular velocity of 360 degrees/sec was 360/5=72 degrees/sec as illustrated in fig. 5. As a result, calculated gear ratios can be validated through simulation. In this case, the example simulation was performed in Creo Mechanism 3.0.

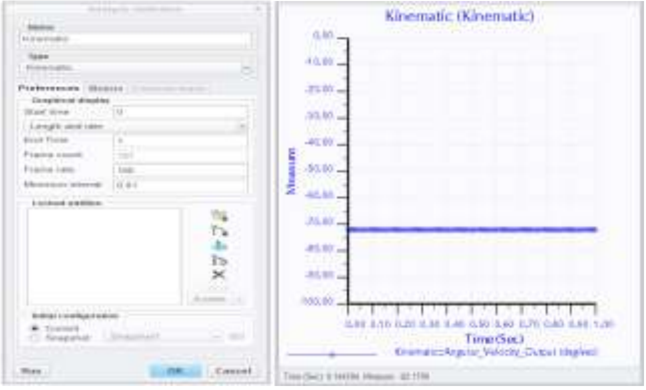

Fig. 5 Creo Mechanism Kinematic Analysis Setup and Angular Velocity Output

IV. CONCLUSION

Overall, the research study was to develop a prototype of an actuator arm that was based on the technology of a Single-Board Computer. Due to the scope of the project, the researchers identified two critical area of research for proper operation and design of an actuator arm.

a) An electrical prototype and Python programming code development.
b) A mechanical design and simulation of a compound spur gearbox train for increased torque.

The electrical prototype consisted of a Raspberry Pi, DC motor, Hall Effect sensors, switches, and relays. The software code for controlling the prototype was developed using the open source Python programming language. A compound spur gear design mechanism was selected for increasing the DC motor torque within a confined space. The mechanism allowed for significant gear reductions within a confined space. Moreover, the study provided gear ratio calculations and mechanism simulation for validating the angular velocities of the assembly.

A. *Lessons Learned*

Although the study was a success, the researchers experienced significant challenges during the design and construction of the prototype:

- Erratic behavior of H-Bridge circuitry.
- Temperamental Hall Effect sensor operation.
- Difficulty troubleshooting the completed system.

The following recommendations and insights have been valuable in resolving many of the challenges faced during the research project. The most significant lesson learned was to test each circuit in isolation of each other. First, verify that all the devices function as defined. For example, the Hall Effect sensors were tested separately by means of measuring the voltage change during operation. As a result, proper operation and connectivity were ruled out during code debugging. Push buttons and LEDs were also tested separately for verifying correct operation and connectivity. The LED, for example, was tested by forcing a constant 3.3VDC from the Raspberry Pi (pin #1) to the circuitry. Also, the temperamental behavior of the Hall Effect sensors was resolved by isolating the sensors and testing their operation. Similarly, the H-Bridge circuit would randomly turn on both polarities causing a dead shot of the power supply. The relay board was equipped with status LEDs for relay operation. This allowed for effective troubleshooting by shutting off the 24VDC power to the motor and monitoring the status LEDs. That way, when both sets of relays were energized at once, the power supply would not be shorted or damaged. A separate Python program was developed for testing the H-Bridge circuit. The program consisted of using a 10-second delay resulting in reversing the motor direction continuously. While running the test code, it was observed that the erratic behavior of the H-Bridge was because of floating logical states generated from the Raspberry Pi. As a solution to the random logical states of the GPIO pins, the final prototype code was refined to logically force the pins to a relay off state prior to executing the program loop.

B. Future Work

Due to the scope of work, the project was limited to the electrical control prototype and the design and simulation of the gearbox train of a patient lift actuator arm. Future work will consist of constructing and testing the actuator arm, which will consist of adjustable limit sensors for maximum and minimum range settings. Various sensor technologies will be incorporated to improve patient handling and safety. These will include optical sensors for sling security, load cells for over-weight verification, proximity sensors for clearance checks and collision detection, and tilt sensors for stability of operation.

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