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Research Article

Design and Manufacturing of Zero Gravity Electric Manipulator

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Abstract

Manipulators are used in industries to reduce the human effort for doing their day to day work. This paper deals with design and manufacturing of a Smart Manipulator - The Zero Gravity Electric Manipulator. The Zero Gravity Electric Manipulator would be able to negotiate the load as, an electrical hoist, pneumatic manipulators or electric actuator does. But with some contradiction as, it allows the operator to move the load as desired on a free path. The Ardunio Uno based motor control system has to be designed and to be implemented along with the necessary actuation system. The proposed system will have the obvious advantages over the traditional pneumatic or electric based manipulator for its compactness, better response time, low maintenance, less complexity involved in load changes etc.

Keywords: *BLDC motor, Worm Gearbox, Ardunio Uno, load cell, Instrumentation amplifier.*

1. Introduction

Material handling process is an integral part of all the industrial processes. Right from the arrival of the raw materials in the industry, till the dispatch of the final product handling system plays a significant part. There are varieties of material handling systems available with manual, semi-automatic or fully automatic operating nature.

Industries can option for fully automated material handling system when the locations of the materials to be handled are fixed and their travel path is fixed. But when it comes for handling the materials whose locations are not fixed and their travel path is not the same all the time, then the involvement of the human operator has to be consider. So in such cases the semi-automated material handling system has to be used. Concentrating on the industrial manipulators; they can be defined as the assemblies which are used to manipulate the location of the material without having direct contact of the operator with the material of the interest.

Presently pneumatic manipulators and electric manipulators are widely used in industry. With the comparison of the electric manipulator and the pneumatic manipulator; the earlier comes with the obvious advantage of compactness; as the pneumatic manipulator of same load lifting capabilities are much bulkier, also when it comes about the efficiency, the electric hoist have comparatively more efficient operation than the pneumatic manipulator. There is need of using a counter weight with the pneumatic manipulators for getting their desired functionality; while such necessity is, mostly excluded in electric hoist.

The smart electric manipulators are now becoming popular these days. These manipulators will negotiate the load as the above mentioned manipulators do, but it allows the operator to move the load as desired on a free path. This dissertation is on the designing of the motor control system for such smart zero gravity electric manipulators.

2. Literature Survey

The PWM method of controlling the speed of the BLDC motor is being used commonly. The hysteresis band is present for varying the duty cycle of the PWM wave (J.E.Muralidhar *et al*, 2014).

The BLDC motor requires six-step inverter bridge configuration for its operation. Against this conventional scheme, there is an excitation scheme of the BLDC motor, using a four switch three phase inverter. This reduces the number of MOSFET switches which in turn reduce the associated amount of switching losses. The EMI is reduced; complexity of the control is reduced improving the performance (M .S. Aspalli *et al*, 2015).

Paper by Masataka Miyamasu, Kan Akatsu, titled 'Efficiency Comparison between Brushless DC Motor and Brushless AC Motor Considering Driving Method and Machine Design' gives the merits of the selection of the BLDC motor against the conventional motors. It provides the comparison of the BLDC machines verses the BLAC machines (Masataka Miyamasu *et al*, 2011).

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In the paper entitled 'Design and Development of Novel Weighing Scale System' gives the weight measuring techniques using the load cell. The signal conditioning requirement of the load cell i.e. using instrumentation amplifier for the conversation of double ended signal to the signal ended, is mentioned in details here. The necessity of the implementing a digital filter in the microcontroller is seen (Kunal D. Gaikwad *et al*, 2013).

Paper entitled 'Position control of four switch three Phase BLDC Motor Using PWM control' gives the method of replacing one leg of three phase inverter using capacitors. This again reduces the complexity of the algorithm required on the software side along with simplifying the MOSFET Bridge (D. D. Dhawale *et al*, 2010).

In the paper by Songgi LEE, *et al* 2011 has discussed the applications of electric manipulator. In this research some assembly tasks are manually completed in assembly sequences and high accuracy positioning is maintained. Therefore, a new system in which human workers cooperate with assistant robot complementarily in assembling a heavy mechanical part is designed. This paper also describes the prototype of a gravity compensation mechanism and a gripper employed in this robot. The gravity compensation mechanism is designed to relieve the burden of worker for holding the mechanical part.

The load cell can be classified based on different type of conversion principle. The strain gauge type of load cell is a transducer which converts a force into an electrical signal. The force which deforms a strain gauge element is sensed through a mechanical arrangement. The strain gauge measures the deformation (strain) as an electrical signal when the strain changes the effective electrical resistance of the wire. Strain gauge load cells are the most commonly used in industry and research. These load cells are particularly stiff, have very good resonance values and tend to have long life cycles in application (Ahmad Qandil *et al*, 2015).

Pedro Silva Girao *et al*, 2013 has discussed the domain of tactile sensing in the context of Robotics. The basic aspects related with tactile sensors, including transduction techniques are revisited. The brief analysis of the tactile sensing techniques that follows provides indicators to conclude on the future of tactile sensing in the context of robotic applications.

In this paper the optical touch sensors are also mentioned. They are of two types intrinsic and the extrinsic type. The extrinsic type touch sensors are widely used in the industries because of their ease of construction. Optical sensors are intrinsically safe and are not affected due to the electromagnetic noise generated in the industries.

In the paper R. D. Ankush *et al*, 2013 proposed the system for lifting the load which uses the pair of worms instead of conventional worm and gear system. The main intension behind development of this system is to improve the efficiency of the conventional system and also to improve the reliability and safety of conventional system, also the cost of manufacturing and space requirement is also important for the development of this system.

3. Hypothesis

In most of the assembly lines in the apparel industries, workers are required to handle loads up to 25-30kg frequently, which reduces productivity and deteriorates deadline of shipments with increasing costs. To improve productivity based on the performance of the workers, an efficient handling system for heavy loads is required to be developed. Productivity loss due to fatigue only in handling of heavy loads could be reduced below predefined limit. It is clear that worker's physical fatigue can be reduced to an extent by improving source of physical fatigue in handling heavy loads. To compensate for the fewer workers, overtime hours worked by industrial hourly workers have been on a steady increase for years which increases in physical fatigue can lead to a decrease in the quality of the produced goods.

Standard that determine a safe lifting limit is given by ISO Standard 11228 Part 1: Lifting. This standard has a reference mass for two handed lifting under ideal conditions of: 25 kg for 95% of males and 15 kg for 99% of females.

Table 1 Survey of workers health issues

Body part	**Rate of physical discomfort 0=No discomfort 10= Worst discomfort**			**Task**
	Worker A	**Worker B**	**Worker C**	
Neck	5	7	3	Drilling, tapping, lifting
Left Shoulder	4	5	8	Lifting
Right Shoulder	4	3	7	Lifting
Left Wrist/ hand	1	2	1	Tapping, Lifting
Right wrist/ hand	2	1	3	Tapping, Lifting
Back	7	10	10	Lifting
Left knee	6	9	8	Working by sitting in congested area, lifting
Right knee	6	9	8	Working by sitting in congested area, lifting

The above table shows the condition of three worker's body due to the physical work they are doing. It can be seen that the physical stress caused to lifting conditioning is having impact on the back of the person. All though other parts of the body are also affected by load lifting. It can also be seen from Fig.1 that the efficiency of lifting the load decreases with the increase in the repetition. With the increase in the frequency of the task or the duration of the task the potential risk of injury also increases.

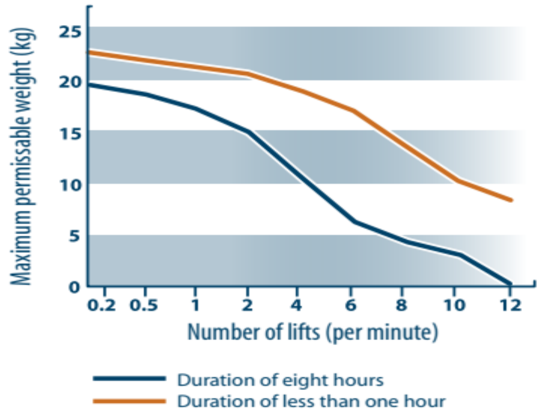


Fig. 1 Efficiency of worker during lifting application

This paper describes a smart manipulator as a solution of the physical difficulties faced by the operators during their day to day work. This smart manipulator will assist the operator to precisely manipulate the load in the desired position and direction, without causing physical stress. This will results in increased efficiency of the operators with increase in the productivity.

With the proposed scheme, provision has to be made where the operator would grip and lift the load. If the operator gradually provides the lifting, the load measurement sensor will find decrease in the measuring load. This would then cause the motor to lift the load vertically upwards. The opposite of the above procedure should also be true then. Depending upon the amount of the force applied by the operator the speed of the motor would be controlled. All of the controlling decision is to be generated by the controller.

The safety of the operator and the human personal working near by the system is also to be taken care off. Even for lifting the load of 25 Kg, the force required for lifting the load will be negligible. With these feature the operator's working efficiency will be increased, with the physical fatigue reduced. Overall this would increase the profit for the company.

4. System Description

Fig. 2 shows the overall block diagram of the proposed system. The Microcontroller block has the control algorithm implemented in the microcontroller. The control system here will allow the zero gravity electric manipulator to perform two modes; namely, the manual mode and the automatic mode which is also called as teach mode. In the former mode the manipulator will just act like a conventional electric hoist manipulator. While with the later one, the controller will decide the response of the motor depending upon the signal coming from the load sensor. The signal coming from the load sensor is continuously been monitored by the microcontroller.

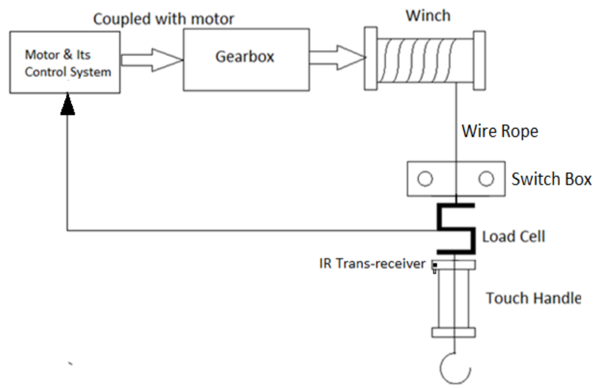


Fig.2 Block Diagram of the proposed system

The BLDC motor is used here. The actuation assembly consists of the gearbox, winch, touch handle. The gearbox is used for assistance of the motor to increase the motor torque. The winch provides the location for wounding the wire rope optimally. The touch handle is provided to sense the operator presence, when the operator grips it. The signal of the touch handle is acting as a safety interlock. The weight measurement block consists of a load cell. The weight of the load is to be feedback to the controller for taking the necessary control decision.

5. Control System

Alternatives for the control hardware could be microcontroller, PLC, LabView and so. But with the motive of making this complete system with minimum cost requirement, microcontroller based control system is optimum choice.

The microcontroller is selected depending upon the number of the inputs and outputs required and the nature of these signals i.e. weather it is analog, PWM or digital in nature. Again the CPU of the microcontroller should be capable of giving the necessary processing speed to handle the designed control algorithm. The stability of the microcontroller for the industrial environment is also a factor to be taken care off. For this reason the microcontroller is to be in a container that is shielded for the industrial noises and the high temperature environment.

Ardunio Uno has a 10 bit ADC, the resolution that it will provide is sufficient for the application. The ENOB will be reduced to 8 bit in worst case of the industrial noise. It has 6 analog input pins and 14 digital I/O pins. The Flash memory of 32KB it provides is sufficient of the application.

The flow chart of the control algorithm is shown in the fig 3. This flow chart is mainly focusing upon the automatic mode of operation of the control algorithm. As in manual mode there is no logical decision is to be taken apart from just rotating the motor clockwise or anticlockwise depending upon the activation of the up pushbutton or down pushbutton.

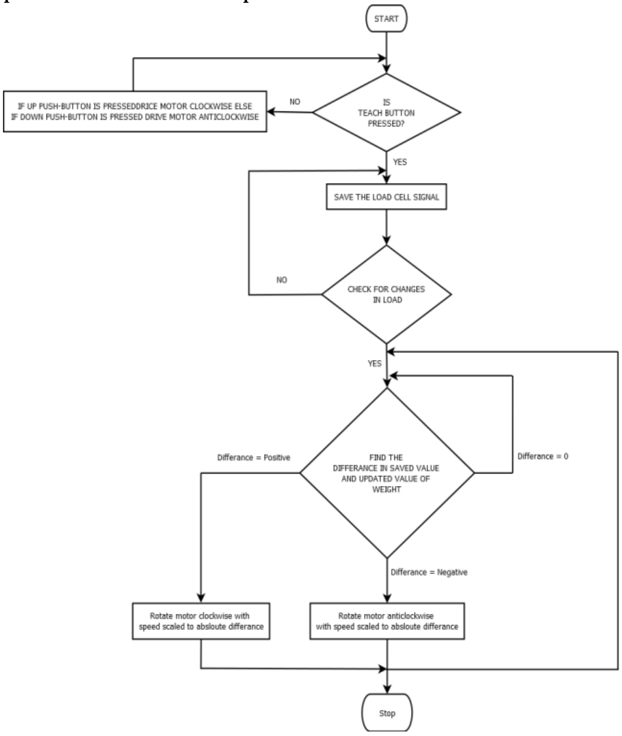


Fig.3 Flow Chart of the Control Algorithm

5.1 The Manual Mode

When the 'Teach' push button is not activated the system goes in manual mode. The movement of the load will depend upon the activation of the respective up or down push-buttons. When none of the push button is pressed then the motor will be disabled and will hold the load in its position.|

5.2 The Auto Mode (Teach Mode)

For enabling the manipulator to be in automatic mode the 'Teach' push button has to be activated. With the actuating of the Teach button; it results in, saving of the load cell signal at that instant and making it as a reference value for subsequent logical computations. The load cell signals coming from the next input scan is then subtracted from this saved reference value. The motor will held its position stationary when the absolute value of the subtracted signal is within the hysteresis band.

Enabling of the motor is interlocked with two conditions, which are logically AND in the controller's algorithm. Firstly, there has to be a positive signal coming from the touch sensitive handle; and secondly, the applied force has to exceed the hysteresis band limit programed in the algorithm.

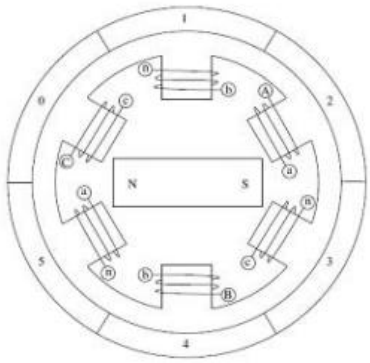
6. Motor Selection

Comparing with the conventional PMDC motor and the induction motor, the BLDC motor has advantages of high performance efficiency, precise variation in speed range, electronic commutation without using commutator and brushes. Control strategies in term of PWM (Pulse Width Modulation) generation and their implementation are more for the speed and direction control of the BLDC motors.

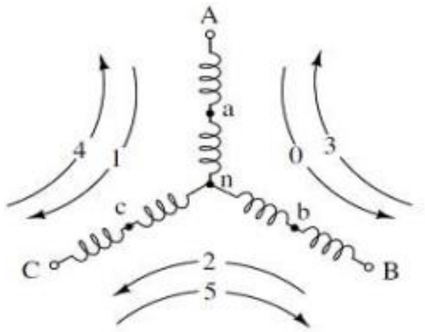
BLDC is an inside out dc motor with respect of its physical construction, as its armature is in the stator and the magnets are on the rotor. There are two main types of BLDC: trapezoidal type and sinusoidal type. In the trapezoidal motor the induced back-EMF has a trapezoidal shape, while its shape is sinusoidal for later for the type. The back- EMF shape depends upon the shape of rotor magnets and the stator winding distribution. Resolution of position sensors (hall-effect sensors) should be high enough for sinusoidal motors as such the knowledge of the rotor position must be known at every instant of time. It also requires more complex software and hardware to assist its operation. The trapezoidal motors, on the other hand are becoming common these days due their simplicity in construction and operation, comparatively lower price and higher efficiency.

Three phase BLDC motor is driven by a three-phase inverter, using which six-step commutation is possible. The conducting interval for each phase is of 120 degree by electrical angle. Each interval starts with the rotor and stator field lines 120 degree apart and ends when they are 60 degree apart. Only two phases conduct current at any instinct of time, leaving the third phase floating. In order to produce maximum torque, the inverter should be commutated every 60 degree so that current is in phase with the back EMF [2].

Fig.4 shows a cross section of a three phase star connected BLDC motor along with its phase energizing sequence. The commutation phase sequence is like AB-AC-BC-BA-CA-CB. Each conducting stage is called one step. The commutation timing is determined by the rotor position, which can be detected by Hall sensors as shown in the figure 2 (H1, H2, and H3) [2].



(a)



(b)

Fig.4 BLDC (a) Motor Cross Section (b) Phase Energizing Sequence

The specific requirements for the system is given below and the motor calculation for the

- Weight (W) = 50 kg.
- Radius Of Drum/Winch (r) = 75 mm.
- Required Lift = 1.5m.
- Linear Travel Speed = 15 m/min. (Maximum Speed)

i. One Rotation Of Winch = 471 mm

ii. Drum Speed = $\frac{15000}{471}$ = 31.84

iii. Gear Box Reduction Ratio = $\frac{\text{Motor Speed}}{\text{Winch Speed}}$ =46

iv. Torque of Motor, for 1500 RPM and drum torque of, the required power is 137.55 W, rounding it off to 180 W, with 24 V supply.

Thus a three phase BLDC motor is selected of 180 W, 24 VDC, 8 A is selected. The selected motor is having a torque of 16Kg-cm.

7. Gearbox Selection

The type of gearbox selected for this manipulator is a worm gear type of Bonfiglioli make. The selection of worm gearbox is done because of its unidirectional power flow feature and its ability of holding its position stationary when the drive force is absent.

The gear box is provided with the reduction ratio of 46. This reduction ratio reduces the speed of the motor but provides with the necessary torque for the application. The mounting of the gearbox is of B3 type foot mounted. Driven shaft of the gearbox is having OD of 22.5 mm with length of 70 mm. The motor is flange mounted with the gearbox.

During the application of the smart manipulator, it is required to hold the position of the load stationary in air. During such circumstance using worm gearbox will assist the control algorithm to execute its decision efficiently.

After the type of the gearbox it comes for the calculation of the reduction ratio, required torque etc. of the gearbox. These calculations must be done by considering the winch physical parameters. The diameter of the winch will be affecting the overall torque and speed provided at the output of the gearbox. The given specifications are as mentioned:

- Maximum weight of the load = 50Kg
- Motor Speed = 1500 RPM
- Maximum linear Travel Speed = 15 meter per minute
- Maximum length of Travel = 1.5 meter
- Winch radius = 75 mm

Taking the radius of the winch of 75 mm. The distance travel in one revolution of the winch will be,

- Distance travel in one revolution = 471.23 mm
- Output RPM of gearbox = 31.83
- Reduction ratio, R of the gearbox = 47.12

This reduction ratio can be approximated to; R = 46, as this is the standard available reduction ratio of the gearbox. Thus the worm gearbox is selected with reduction ratio of 46, for satisfying application need. Further selection of the gear box is taken from Bonfiglioli gear box catalogue.

8. Load Cell

The weight of the material of interest is been measured by the S-shaped load cell. The S-shaped load cell is used specifically here, as it is more sensitive to the axial stress.

The power source and the output signal of the load cell is carried through a shielded cable of 3 meter length. The load cell is power by +5 V supply from the Ardunio. The signal of the load cell is amplified and feedback back to the controller in voltage form. The load cell is provided with IP67 protection.

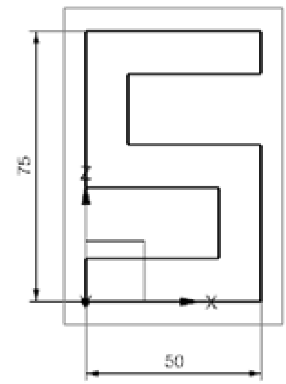


Fig.5 S-shaped Load cell

The dimensional details of the S-shaped load cell are given in fig.5. The load cell is available with four core shielded cable. The red and black core is for supplying power supply to the load cell. While the blue and yellow are the output voltage cable. This cable provides differential voltage as the output. Also the amplitude the voltage at this cable is in millivolts.

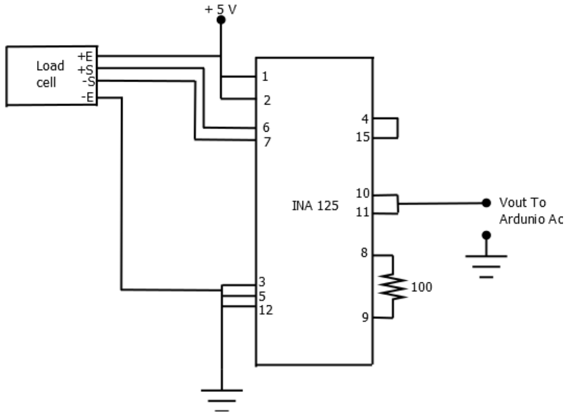


Fig.6 Load cell interface circuit

This signal characterises are not suitable for connecting with the controller. For interfacing such signal to the controller it has to be amplified and converted to signal ended equivalent. Fig.6 gives the circuit diagram of the signal conditioning circuit for the load cell.

9. Touch handle

The touch handle is provided for allowing the operator to have a grip. The handle is provided with a 'Tare Weight' of 1 Kg. This is required to keep the load cell in constant tension even if no load is present on the system. Provision for the placing of the IR trans-receiver circuitry is also provided in the handle assembly. This sensing circuit gives the feature of sensing the operator's hand proximity.

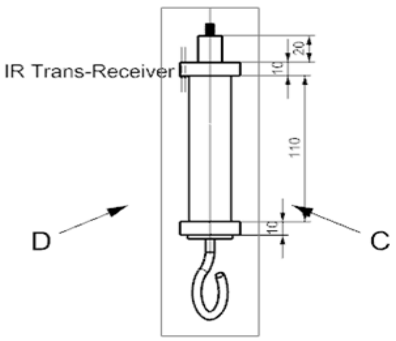


Fig.7 Touch Handle

The optical technology is to be used for sensing the human touch. The IR LED and IR receiver is connected in retro-reflective arrangement. The 100 ohm resistor is made variable to vary the sensing range. The sensing range is kept 5 cm. The LM 358 IC is used as voltage follower. The complete circuit is supplied by 5 V supply. The Fig.8 shows the circuit for the IR trans-receiver. The PCB of the IR trans-receiver circuit is to be placed in the handle assembly at the top of the metal handle.

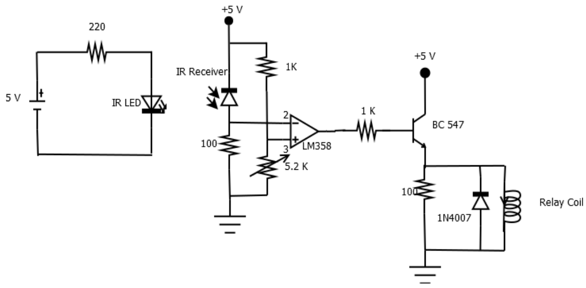


Fig. 8 IR trans-receiver circuit

The output of LM 358 is used to drive the relay. The transistor BC547 is used as a switch here, causing the output to be inverted at the collector end. For the application it is not required to have the output to be inverted. Therefore the relay is connected at the emitter end.

10. Experimentation

The motor control system is integrated with its associated actuation system. The BLDC motor is connected to the Worm gearbox through flange mounting. The complete assembly is wall mounted on the L-shaped bracket. The winch is connected to the output shaft of the gearbox. The Touch handle assembly with Load cell and the tapping of M6 X 1.25 is provided for connecting push buttons for Up, Down, Teach and Emergency operation; is connected to via wire rope to the drum. Hook arrangement is provided for loading and unloading of the weight. Figure 8 shows the 3-D CAD model of the actuation system with the motor assembly.

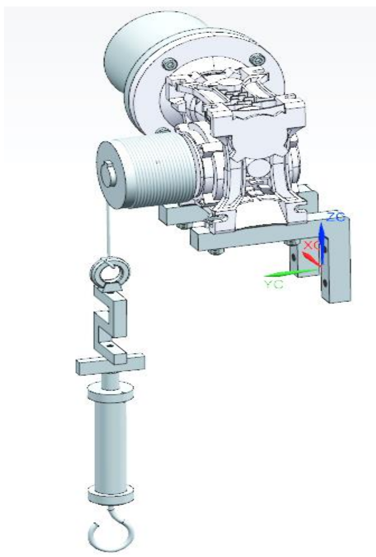


Fig. 9 CAD 3D Experimental Setup Layout

The system is then first tested in Manual mode for the load weight varying from 0-50 kg. Then the system is tested in Auto mode, where the load weight is varied from 0-45 kg. The load cell signal and the touch handle signal from the actuation system are fed back to the motor control system. The complete experimental system is shown in Fig. 9.

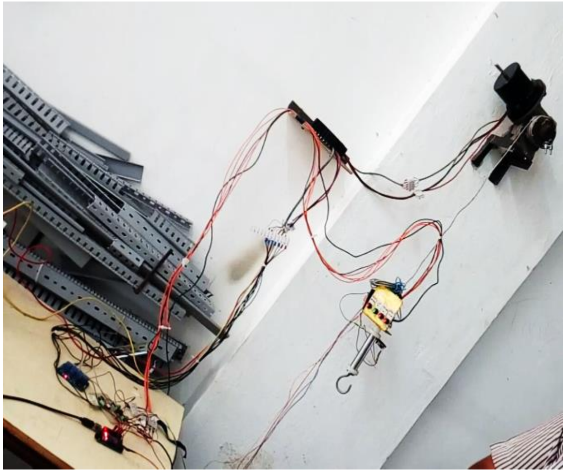


Fig.10 Experimental Setup layout

11. Results and Discussion

The BLDC motor is selected with the Ardunio Uno microcontroller as the control hardware. The motor control system in conjunction with is actuation part is able to manipulate the load of maximum 45 kg in closed loop and 50 kg in open loop. The selection of the worm gear box after the comparative analysis based on specifications, cost and availability lead to a gear box of reduction ratio of 46 for assisting the motor in lifting the variable load of maximum 50 kg. The optimum design of the Winch/Drum assembly with diameter of 70 mm and length of 60 mm gives the optimum drum length for the wire rope required to raise or lower the load. A Touch Sensitive Handle, not only has been designed and manufactured ergonomically to provide a location for the operator to grip it but also to sense the presences of the operator's hand. The load cell signal is varied for weight 0-50 kg giving output 0-5 V DC. The LPF removes the noise present in the load signal output.

During operation, it was found that, in both the modes; if the operates swings the load, it makes the load to oscillate. In order to avoid this action; a 10 K Ohm potentiometer is present at the pivot for finding the direction of the swing, along with a brushed DC motor will just give a twisting force in the direction of the swing.

Initially, the reading of the potentiometer for the current position is considered to be zero. When the operator swings the load, the potentiometer rotates in the corresponding direction. The difference between the initial and the final position of the potentiometer is considered for finding the direction of swing. The DC motor then gives a twist in the direction of the swing, to damp the oscillation. The oscillation of the load will cause the reading of the potentiometer to fluctuate accordingly. When the oscillation drops below the hysteresis limit, the reading of the potentiometer will be consider as zero for that instant again.

The safety aspects of the system considering the signal coming from the load cell and the hysteresis band in the software are taken care off. The motor draws inrush current of around 6.8A at full load. The current drawn during lifting up at 50 Kg load is around 5.3 A, and the current drawn when the motor is lowering down is around 4.1 A. The speed of linear travel of the motor is 13.8 m/ min.

Conclusion

The smart manipulator- 'The Zero Gravity Electric Manipulator' has been developed as the outcome of this dissertation. The operator has been actively involved in the decision making of the manipulator's operation comes out as the significant feature of this smart manipulator. The ability of the designed motor control system to manipulate the material for its position, velocity and braking is an attractive alternative for the conventional electric or pneumatic manipulator used in the industry.

Table 2 Survey of workers health issues

Body part	Rate of physical comfort On 0-10 scale			Task
	Worker A	Worker B	Worker C	
Neck	8	7	9	Drilling, tapping, lifting
Left Shoulder	10	7	8	Lifting
Right Shoulder	9	8	10	Lifting
Left Wrist/ hand	9	9	10	Tapping, Lifting
Right wrist/ hand	8	9	9	Tapping, Lifting
Back	7	10	9	Lifting
Left knee	8	9	7	Working by sitting in congested area, lifting
Right knee	7	10	9	Working by sitting in congested area, lifting

The results shown in the above table advocates the successful accomplishment of the planned hypothesis for this paper. With this manipulator the physical discomfort faced by the operator has been significantly reduced. Also the operators are now able to work more efficiently for lifting the heavy loads in the company during their working hours, reducing the cycle time of the operation.

Future Scope

The control system can be more purified by replacing the controller hardware of Ardunio Uno with the PLC. The objective of achieving the desired control system with minimum coast can be achieved by going for the mass production of the Zero Gravity Electric Manipulator. The difficulties of having changing voltage potential throughout the electrical circuit would be overcome here by using the PLC as the control hardware.

With both the control hardware i.e. either using Ardunio Uno or PLC it is possible to connect the Ethernet and interface the system with the industrial line. It is possible to get the necessary data of the operation from the system and have the record of it.

The use of wireless signal transmission of the load cell and the IR sensor would eliminate the wiring required in the touch sensitive handle. Using such wireless sensor shall prove to be a cost effective especially when the project shall be taken up for mass production. This shall minimize the signal noise interference usually an issue in the industrial environment.

References

http://www.worksafenb.ca/docs/MANUALEdist.pdf

J.E.Muralidhar, P.Varanasi, (2014) Torque Ripple Minimization & Closed Loop Speed Control of BLDC Motor with Hysteresis Current Controller, IEEE.

M.S. Aspalli, Farhat Mubeen Munshi, Savitri. L. Medegar (2015) Speed control of BLDC Motor with Four Switch Three Phase Inverter using Digital Signal Controller, IEEE.

Masataka Miyamasu, Kan Akatsu, (2011) Efficiency Comparison between Brushless DC Motor and Brushless AC Motor Considering Driving Method and Machine Design, IEEE.

Kunal D. Gaikwad, Dr. P. B. Dahikar, (2013) Design and Development of Novel Weighing Scale System, International Journal of Engineering Research & Technology.

D.D.Dhawale, J.G.Chaudhari, Dr.M.V.Aware, (2010) Position control of four switches three Phase BLDC Motor Using PWM control, Third International Conference on Emerging Trends in Engineering and Technology, IEEE.

J.P. Holman. "Experimental Methods for Engineers". Eight Edition.

Songgi LEE, Xin JIANG, Koyu ABE, Satoko ABIKO, Atsushi KONNO and Masaru UCHIYAMA, (2011) A Human Assistant Robot System for Handling Heavy Mechanical Parts in Assembly Lines, SI Internal, IEEE.

Ahmad Qandil, Adnan I. O. Zaid, (2015) Consideration in the design and manufacturing of a load cell for measuring dynamic compressive loads, IEEE.

Pedro Silva Girao, Pedro Miguel Pinto Ramos, Octavian Postolache, José Miguel Dias Pereira, (2013), Tactile sensors for robotic applications, Elsevier, Measurement 46 1257–1271.

R. D. Ankush, Prof. P. D. Darade, (2012) Review on Application of Worm Pairs in Load Lifting Devices, Volume 1 Issue 4, JETIR.