Design and prototyping of an accelerometer based parallel manipulator for endoscope position control

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ABSTRACT

The advancement of embedded controllers in minimally invasive robotic surgery (MIRS) provides an innovative and safe alternative to traditional open surgery. This paper illustrates the Accelerometer-based Embedded prototype of 4 link novel parallel manipulator design and endoscope end position control scheme. The parallel manipulator proposed is of 4 leg quadra model with 4 servo actuators to drive the end effector to which endoscope camera integrated with micro electro-mechanical system (MEMS) accelerometer. The parallel manipulator is modeled in Coppeliasim computer-aided design (CAD) and embedded control logic is implemented in the ATmega328P microcontroller. The achieved end effector movement is +/- 10 cm from the ground clearance validated it in CAD tool. The potentiometer-based position control of the endoscope and its image magnification is recorded. The internet of things (IoT) infrastructure extension to the demonstrated protype is proposed. This cost-effective model is compared with the existed models available in the market.

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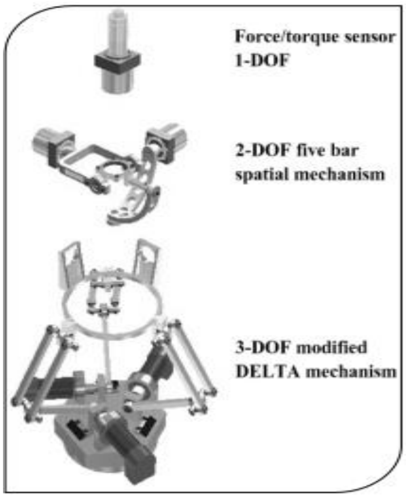
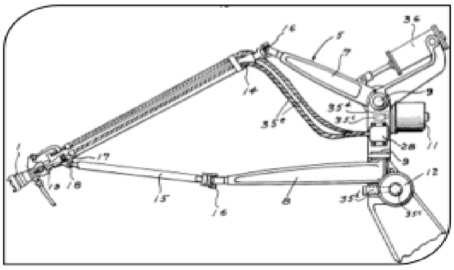
1. INTRODUCTION

In recent years need for parallel manipulators (PM) for laparoscopic and endoscopic surgeries increasing due to the safe and innovative alternatives to traditional open surgery, the advantages of minimally invasive operation, it promises fewer incisions with pain, offers a low risk of infection, fast recovery period and almost no scarring. The Assistance of a parallel manipulator provides surgeons greater control, better access to the area of operation. The defined structure of PM is an actuator of the base connected to the end effector via kinematic links [1], [2]. The first implemented parallel manipulator was reported by American inventor Willard L.V Pollard for his patented work of spray painting in 1938, in 1960, Gough and white hall proposed six linear jack machines for tire testing application. In 1980, Stewart designed and developed a work surface to be used for flight simulators. Figure 1 represents various degree of freedom manipuators are often used in surgical operations. Figure 1(a) depicts the 1, 2, and 3-degree of freedom (DOF) parallel manipulators and Figure 1(b) and Figure 1(c) shows Pollard and spatial models. The PM potential applications are in the field of pick and place, sorting the goods for material handling, mining machines, space applications like antenna orientation, Hepatic devices, and telescopic positioning systems [3]-[5].



(a)



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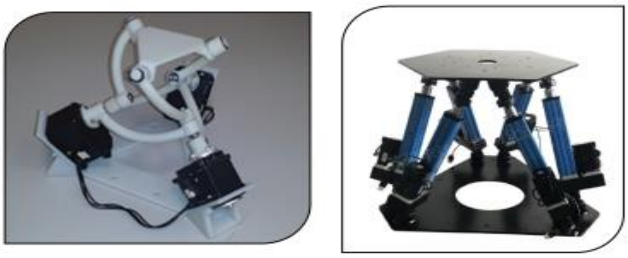

(c)

Figure 1. Various Parallel manipulators with different DOF, (a) 1, 2, and 3 DOF parallel manipulators, (b) pollards manipulator model, and (c) spatial and hexpod 6 DOF parallel manipulator

3-degree of freedom (3-DOF) parallel manipulators for minimally invasive surgery are the current trend, structurally parallel manipulators (PM) are well suited for robotic-assisted surgeries due to their inertia and stiffness compared to serial manipulators. The traditional 3-DOF parallel manipulators are popularly called delta robots, (need to write drawback of 3-DOF) [6], [7]. Concerning steward platform design, many multi DOF, greater than 3, 4 and 6 leg mechanisms have been proposed. The 6 and above DOF parallel manipulators have drawbacks in terms of small workspace, mechanically complex in design, movement complexity and its control, complex kinematic analysis. These shortfalls trigger more exploration in minimum DOF manipulator design, as a result, the applications in the industries are spreading in multiple domains day today. There are enormous success stories of parallel manipulator making moments effectively in ASEA Brown Boveri (ABB) make Flex picker as pick and place tool, two-arm robotic ortho surgery as shown in Figure 2. The 3-DOF PM has a wide choice for many industrial applications, however, due to limited functionalities in terms of translation capabilities many industries are looking for new PM designs with 4-DOF PMs [8], [9]. The class of 4-DOF is called H4 could be used for better precision and accelerated application like pick-n-place and in robotic surgeries. Usually, the H4 configuration offers 3-DOF translations and 1-DOF rotation moment of its axis. The 4-DOF PMs due to their parallel mechanism best suited for accelerated applications promises high performance in critical scenarios. The existed 4-DOF PM are Rolland designed model, Manta and Kanuk, Zhao and Huang, Huang and Li invented model at Zhen Huang Robotics Research Center Yanshan University Qinhuangdao [10], [11]. The paper presents the modeling of 4-DOF parallel manipulator with coppeliasim which is customized computer-aided design (CAD) software. The proposed 4 leg quadra parallel manipulator is designed based on a practical embedded model is imitated in the Coppeliasim software simulator to obtain forward and inverse kinematic parameters.

Parallel manipulators in the medical domain, nowadays robotic-assisted surgery progressively increasing due to the success rate, the robotic-assisted laparoscopic surgery is one, the surgeon operates over the body using the assistance of robot with a controller [12]-[14]. The robot mimics the motions of the surgeon, make the process Master and slave system, due to the requirement of high accuracy in mobility and accessibility of tools at the critical areas, it’s an obvious decision to rely on Motor controlled mechanism [15]. The scope of using robotic manipulator is oncology, urology, thyroid and colon, and rectal fields of surgeries. The ability to move 360 degrees offers better precision and skill, a camera mounted at the tip of laparoscopy provides clear visualization of the operated area. The process is portrayed in Figure 3, experimental observation on human surgery versus robot-assisted surgery results proved that more motion stability is achieved with a parallel manipulator-based robot [16], [17].

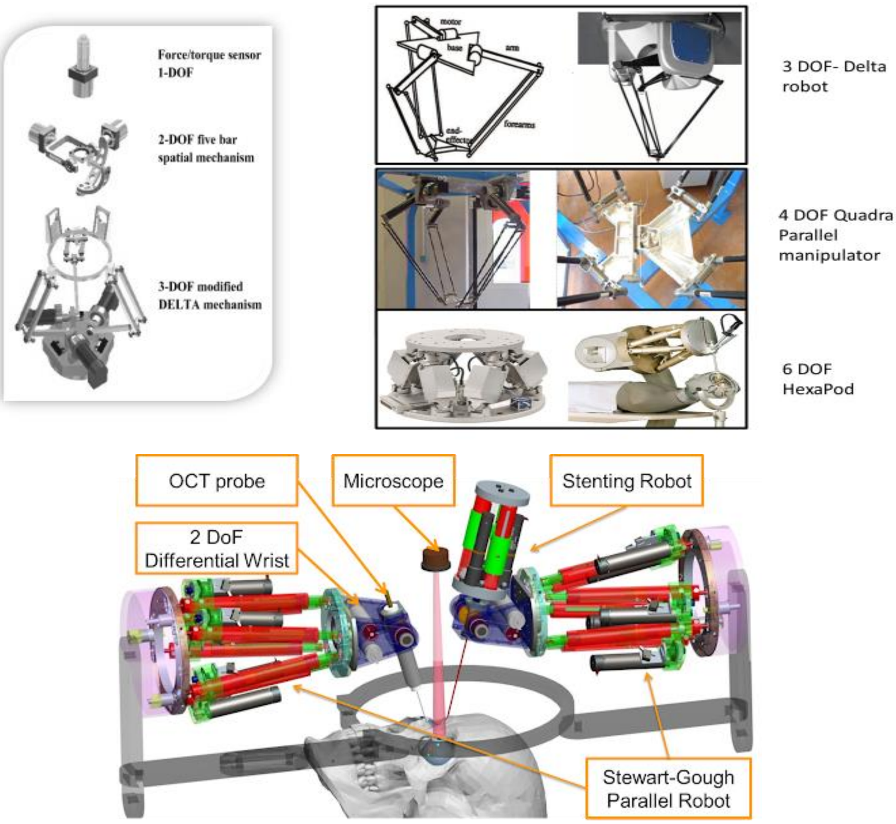

Figure 2. 2-3-4 and 6-DOF surgical assisted parallel manipulators

Figure 3. Robotic assisted surgery mechanism

2. METHOD

The 4-DOF parallel manipulator has a PLUS structured base to locate the servo actuators in an aligned position. The servo motors actuated the kinematic links connected to the end effector; the selected end effector is circular in shape. The structure has 3 joints and 2 links for each servo to end effector connection. Total joints and links for the 4-DOF models are 12 and 8. Figure 4 imitates the actual hardware prototype of quadra parallel manipulator modeled in Blender software with consideration of hardware dimensions of Base and end effector plates, upper and lower links, and servo motors.

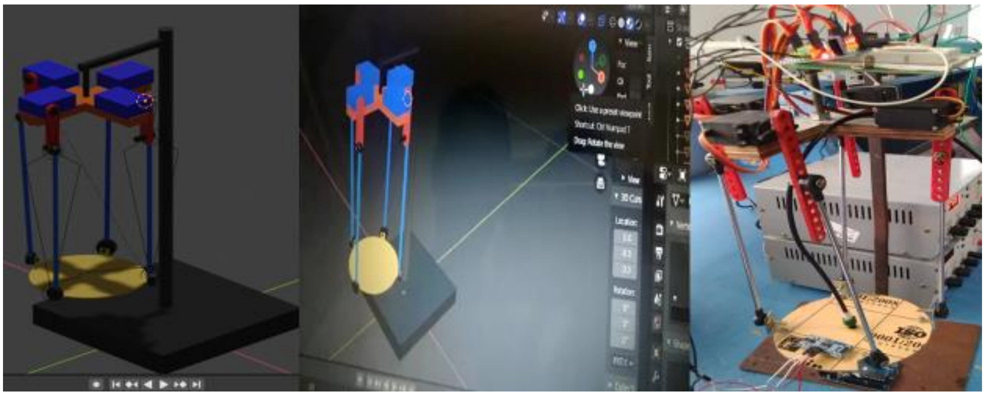

Figure 4. Four leg quadra parallel manipulator CAD and hardware model

Modeling of quadra parallel manipulator: coppeliasim model of the proposed manipulator is portrayed in Figure 5. The Dimensions used to create model structures are listed above in Table 1. The operated modes of the 4 leg model are described with A, B, C, and D modes of operations. The forward and inverse kinematics helps to understand the relative moments of the end effector concerning the actuator angles. In the mode, an operation end effector is intended to move up and down movement, the inverse kinematic engine drives the actuators to the corresponding angle. ϴ1, ϴ2, ϴ3and ϴ4 angles of servo decides the final movement of the end effector in the vertical direction, i.e., Z-axis as per the model Cartesian system. X, Y, Z are the end effector tip position, the observations made are all the servo motor angles to the same and proportionally changes to achieve linear movement in Z directions. In mode, B & C Motor angles are oriented in such a way that the end effector follows left and right curve paths. In mode D operation motor angles are confined to trace a linear planar movement at the end effector can be seen in Figure 6.

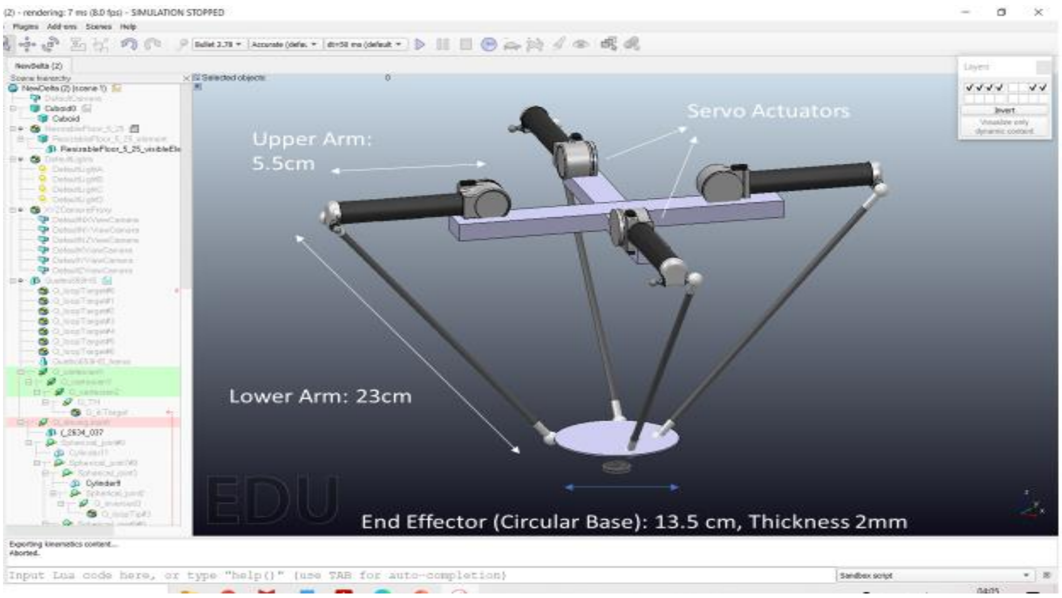

Figure 5. Dimensions of 4 Leg quadra parallel manipulator

Table 1. Characteristic dimensions of 4 leg quadra parallel manipulator prototype model

	Features of manipulator
Property Symbol:	Plus Model (Actuator support) End effector as Circular shape
Platform Diameter	13.5 cm and Thickness of 2 mm
Ground clearance	approx.(1 Feet, 30 cm)
Lower link length	23 cm
Upper link length	5.5 cm

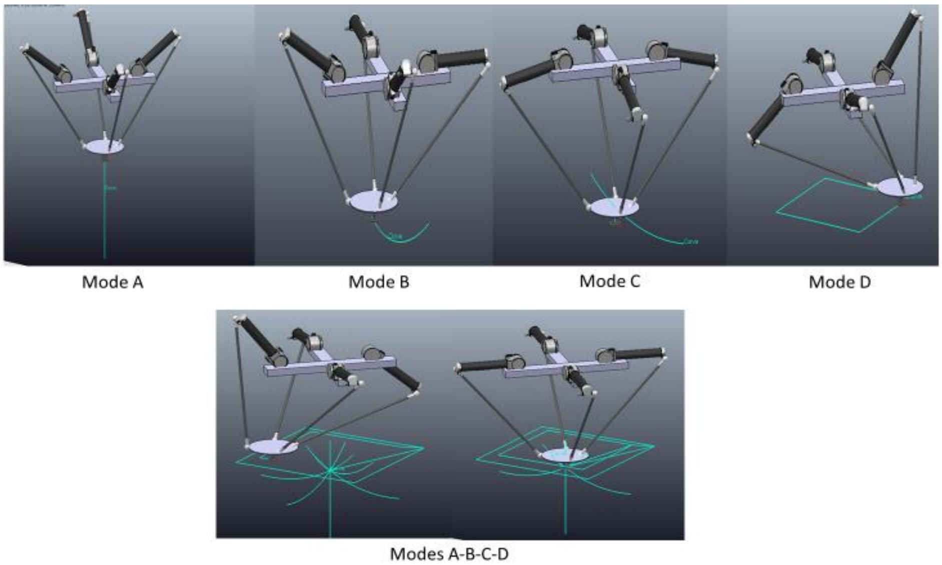

Figure 6. Four modes of movement of end effector from copelliasim simulator

The absolute position of the end effector in the Cartesian coordinate system is graphically represented, the position versus time plot and velocity and orientation are observed from Figure 7 and Figure 8. The simulation took 25 seconds to complete the 4 modes of operation. The three different color graphs depict absolute positions in the X, Y, and directions [18].

The velocity profile helps in estimation of how quick the model accelerates to the desire position from the Figure 8, three colored graph represents end effector velocity three directions in meters per second. The Selected components for the hardware implementation are wooden structures with simulated dimensions provided in Table 1. Two sets of plants one has PLUS structure so that the mounted servo motors MG995 which has 4.8 V operating voltage, 9 kg/cm stall torque, pulse width modulation (PWM) controlled based command signal, can move freely without intersecting with other motor links, the end effector is a circular plate of thickness 2 mm, has few hole provisions to mount endoscopic camera and ultrasonic sensor. The actuator platform and the end effector are connected with two links and have 3 joints for one actuator to move the base. There are 4 servo actuators that offer 4 legs to movable base via 8 links and 12 joints as shown in Figure 9.

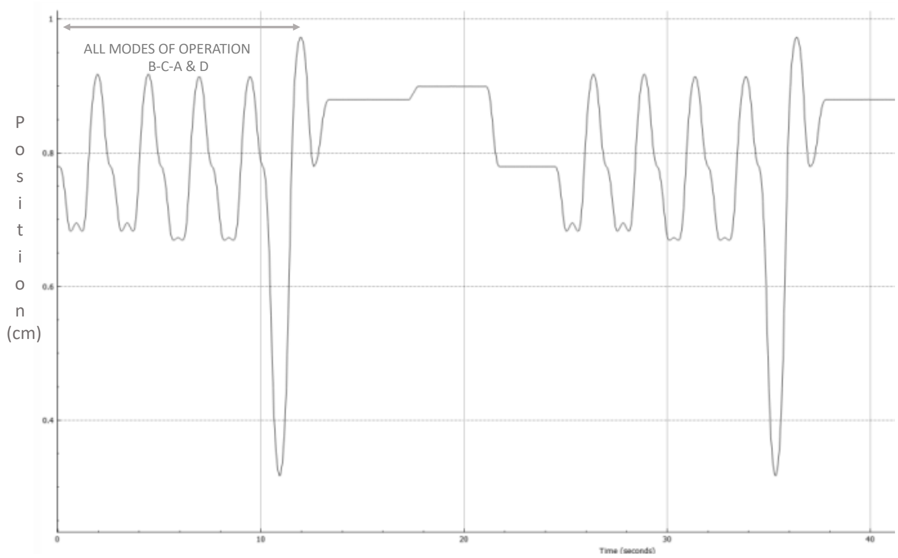

Figure 7. Position Profiles of 4 leg quadra parallel manipulator

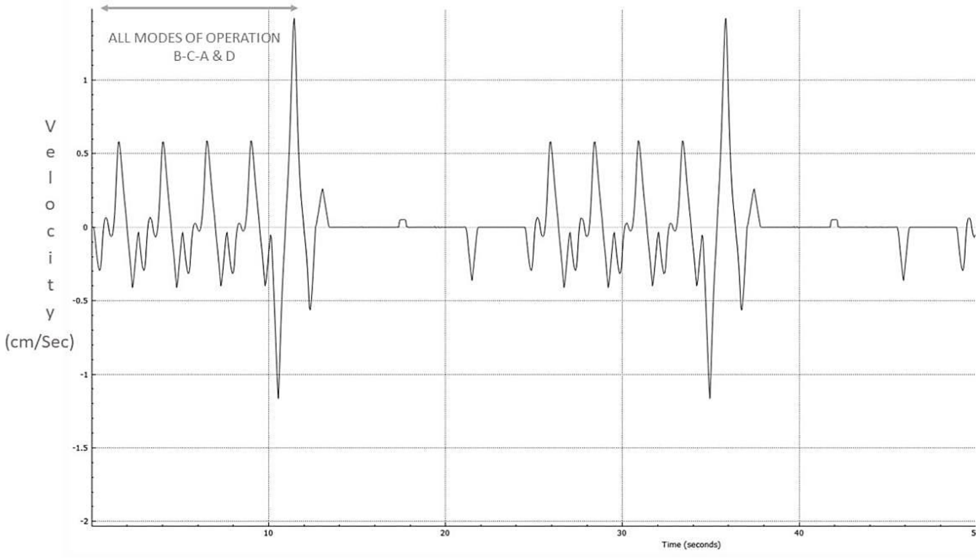

Figure 8. Velocity profile of the end effector for 4 modes of operation

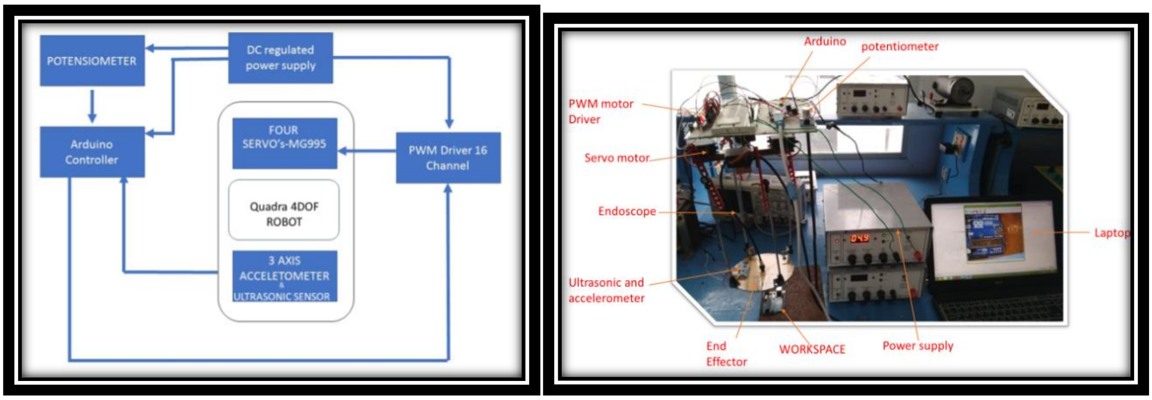

Figure 9. Block diagram and hardware prototype of 4 DOF parallel manipulator

The Servo motors are connected to the 16 channel PWM driver, to maintain motor sustainability during the actuation process further the embedded controller experiences minimum motor driving burden through PWM signal generation. The embedded controller is used to attain the control logic for various modes of operation described in the simulation process. The wiring diagram is represented in Figure 9, a potentiometer is used to control the position of servo via generation of pulse width modulated signal. Using the Arduino integrated development environment (IDE) environment, the map function is used to generate the position-based duty cycle via 16 channel drivers [19]. The potentiometer angel 0 to 270^{o} degrees produced a servo angle of 20 degrees to 170 degrees. A 3-axis micro electro mechanical systems (MEMS) accelerometer is mounted on the surface of the end effector to get the reverse kinematic control of actuator angle adjustments for better platform stability which is a primary characteristic of a surgeon-assisted robot for precise movements [20]. The feedback control scheme is designed based on the base platform location from the ground level through the ultrasonic sensor HC SR04, which triggers the ultrasound of 25000 Hz, an echo generates due to obstacle detection in return generate a pulse. The time interval between the ultrasound triggering and eco receiving is used to calculate the obstacle distance in terms of centimeter or inch. Figure 10 is a pictorial representation of a flow chart for inverse kinematic implementation in which MEMS accelerometer and ultrasonic sensor data in comparison with the base reference values to tune the servo angle. The open-loop and closed loop scheme are achieved to locate the end effector to the desired position (10 cm from the ground level) [21], [22]. The cost of prototype includes the servo motors 4000 INR, 16 channel driver 500 INR, carbon round hinged connecting rods 3000 INR, embedded programmable board 500 INR, camera module 2000 INR, Potentiometer 500 INR.

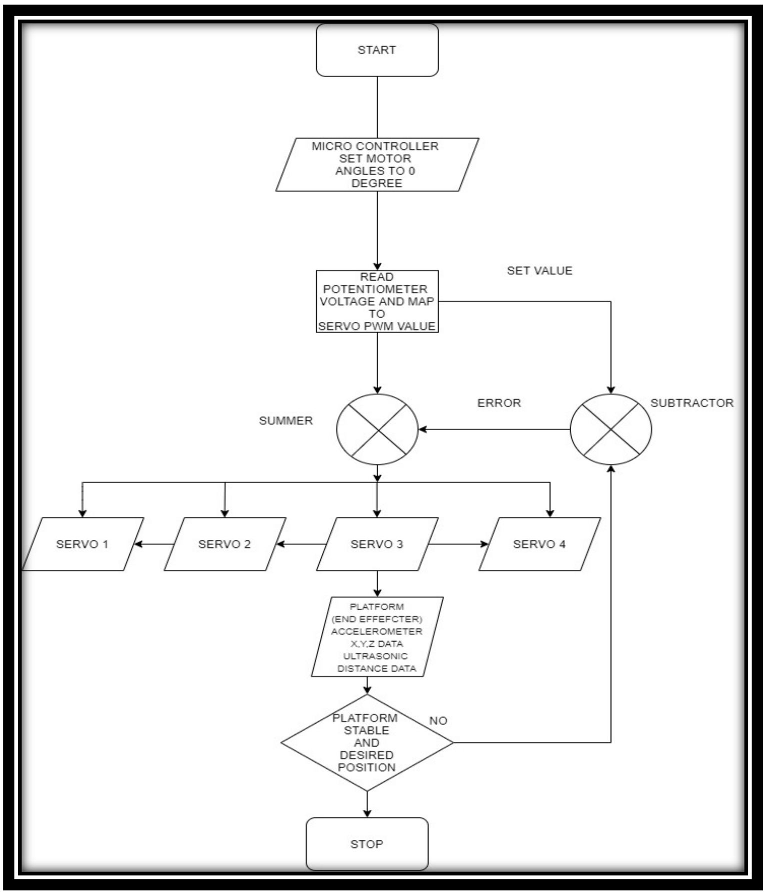

Figure 10. Flow chart for position feedback for platform form stabilization

3. RESULTS AND DISCUSSION

The CAD modeled 4 DOF manipulator using simulator obtained the position, orientation, and velocity profiles. The absolute position in X, Y, and Z direction range from 0-20 cm, and the orientation Pitch, roll, and yaw as 2 degrees with respect to the reference. Velocity profile provided the accelerated model, with 2 meter in a second speed. The experimental setup is intended to obtain the 4 DOF end-effector position using the HC-SR04 distance sensor, the obtained vertical sweep of 20 cm in z-direction using the open-loop control of the potentiometer, the reverse kinematic approach is attained experimentally using the position feedback. Figure 11 illustrates the magnified view end effector through an endoscope connected to its center. An embedded Arduino board is placed beneath the end effector considering it a workspace, its position at 10 cm and 12 cm, magnified images are snapped. The MEMS accelerometer X Y Z position is obtained at the serial monitor infer the stability of the end effector, X-norm- ranges -3.05 to -3.07, Y-norm 1.87-1.93, and Z-norm 9.2-10.22 for the movement of 12 cm to 10 cm vertical displacement of manipulator movable base. The scope of extending the details of the accelerometer to monitor the parallel manipulator end-effector position wirelessly using the internet of things (IoT) feature, in which Wi-Fi enabled embedded controller Node-MCU, is used to record the data from the accelerometer with a baud rate of 14400. The Think speaks online cloud services provide an application programming interface (API) key for writing the accelerometer data into the cloud and retrieve them from the cloud [23]. The data visualization package provides the access to real-time data graphically as we obtained in the simulator remotely. This IoT model shown in Figure 12 is the promising surgeon to operate the patient remotely with robotic parallel manipulator assistance. The extendibility of the model objective with added feature of speech-based position control of endoscope position via servo motor angles adds value addition doctor who operates for the effective surgical support. He demonstrated 4 link parallel manipulator offer singularity in motor operation [23], with accelerometer-based end effector stabilization for endoscope integrated to the platform [24]. The module may assist the surgeons for precise view of human body interior during the operations where the optimal camera gaze 10 cubic centimeter spherical volume. The module controllability can be extended through voice commands using IoT module connectivity [25].

Figure 11. The Endoscopic magnified view with position feedback of ultrasonic sensor

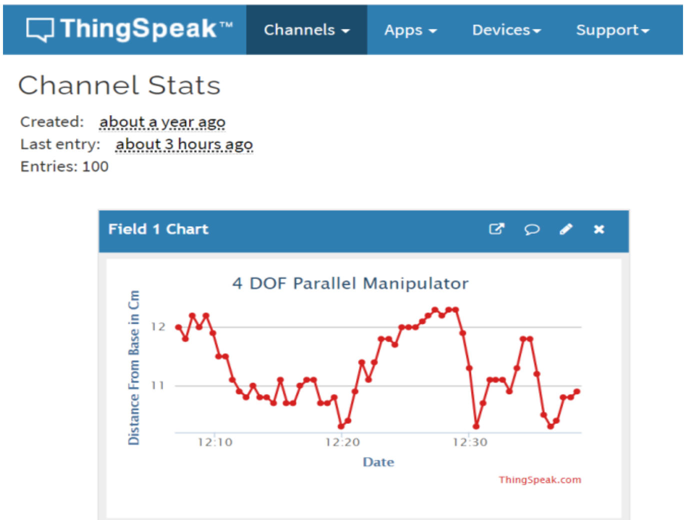

Figure 12. IoT cloud Console for 4 DOF parallel manipulator

4. CONCLUSION

The proposed novel 4 leg quadra parallel manipulator is CAD Modeling in Blender with the specification as that of hardware. The Coppeliasim simulator provided the position, velocity, and orientation curves, they infer the model prosed is stable with the dimensions and observed its operation in 4 modes i.e. linear, planar, left, and right curvy moment. The platform end effector kinematic and dynamic data are recorded. The imitation of the CAD prototype is achieved structurally and operationally using 4 servo-based embedded controllers with position and stability parameter feedback. The inverse kinematic scheme is proposed and implemented with satisfactory results. The prototype is cost-effective in terms of using the customized components like servo, PWM driver, and HC-SR04 easily integrable with Arduino. The crucial characteristic of accuracy, stability, and reachability to the critical area is examined, as the real-time minimally invasive surgeries lack less operating space to a tool, the effective movement +/- 5cm in all the direction is achieved with the proposed model. The Model has flexible to adapt speech/voice-based control for effective movement monitoring for the users.

REFERENCES

[1] K. Kawashima, T. Kanno, and K. Tadano, "Robots in laparoscopic surgery: current and future status," *BMC Biomedical Engineering*, vol. 1, no. 1, p. 12, Dec. 2019, doi: 10.1186/s42490-019-0012-1.

[2] Q. Li and Z. Huang, "Type synthesis of 4-DOF parallel manipulators," in *Proceedings - IEEE International Conference on Robotics and Automation*, 2003, vol. 1, pp. 755–760, doi: 10.1109/robot.2003.1241756.

[3] A. Pandian, M. V. Rishika, M. Sudakshina, and M. S. V. R. Karthik, "Control technique for power electronic converter in hybrid electric vehicle," *Journal of Advanced Research in Dynamical and Control Systems*, vol. 12, no. 2, pp. 35–42, 2020, doi: 10.5373/JARDCS/V12I2/S20201005.

[4] V. K. Mangalagiri, N. S. Gujar, and P. S. Varma, "Digital automation in monitoring of life test setup of LED lamps using embedded systems," *International Journal of Innovative Technology and Exploring Engineering*, vol. 8, no. 6, pp. 1630–1634, 2019.

[5] R. Bade, B. V. Ramana, and K. Dusarlapudi, "A six servo six DOF position-controlled platform for sorting application'," *International Journal of Engineering and Advanced Technology (IJEAT)*, vol. 8, no. 4, pp. 1215–1219, 2019.

[6] H. J. Kadhim and M. J. MohammedAmeen, "Design and implement a smart system to detect intruders and firing using IoT," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 6, p. 5932, Dec. 2020, doi: 10.11591/ijece.v10i6.pp5932-5939.

[7] M. T. Torres, R. C. Ruiz, P. V. Chable, J. G. V. Dimas, and A. O. Diaz, "Performance of compliant mechanisms applied to a modified shape accelerometer of single and double layer," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 6, p. 4675, Dec. 2019, doi: 10.11591/ijece.v9i6.pp4675-4683.

[8] M. Susmitha and D. S. Reddy, "Home automation rely on wifi," *International Journal of Applied Engineering Research*, vol. 12, no. Special Issue 1, pp. 595–601, 2017.

[9] S. Chundhu, K. Dusarlapudi, V. S. K. Narayanam, and K. N. Raju, "Novel programmable solar based SIMO converter for SMPS applications with IoT infrastructure," in *Lecture Notes in Electrical Engineeringthis*, 2022, doi: 10.1007/978-981-16-7985-8_107.

[10] A. H. Ahmed, M. N. A. Al-Hamadani, and I. A. Satam, "Prediction of COVID-19 disease severity using machine learning techniques," *Bulletin of Electrical Engineering and Informatics*, vol. 11, no. 2, pp. 1069–1074, Apr. 2022, doi: 10.11591/eei.v11i2.3272.

[11] K. Dusarlapudi and K. N. Raju, "Embedded prototype of 3 DOF parallel manipulator for endoscope application using 3 axis MEMS accelerometer," *Journal of Advanced Research in Dynamical and Control Systems*, vol. 12, no. 2, pp. 1225–1235, 2020, doi: 10.5373/JARDCS/V12I2/S20201158.

[12] B. K. Patle, G. Babu L, A. Pandey, D. R. K. Parhi, and A. Jagadeesh, "A review: On path planning strategies for navigation of mobile robot," *Defence Technology*, vol. 15, no. 4, pp. 582–606, Aug. 2019, doi: 10.1016/j.dt.2019.04.011.

[13] B. K. Patle, D. R. K. Parhi, A. Jagadeesh, and S. K. Kashyap, "Matrix-binary codes based genetic algorithm for path planning of mobile robot," *Computers and Electrical Engineering*, vol. 67, pp. 708–728, Apr. 2018, doi: 10.1016/j.compeleceng.2017.12.011.

[14] Y. S. Kwoh, J. Hou, E. A. Jonckheere, and S. Hayati, "A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery," *IEEE Transactions on Biomedical Engineering*, vol. 35, no. 2, pp. 153–160, 1988, doi: 10.1109/10.1354.

[15] M. Preeti, K. Guha, K. L. Baishnab, A. Sastry, K. Dusarlapudi, and K. N. Raju, "Analysis of a proof mass structure of a capacitive accelerometer as wearable sensor for health monitoring," in *Lecture Notes in Electrical Engineering*, vol. 781, 2022, pp. 315–327, doi: 10.1007/978-981-16-3767-4_30.

[16] L. Ott, F. Nageotte, P. Zanne, and M. D. Mathelin, "Robotic assistance to flexible endoscopy by physiological-motion tracking," *IEEE Transactions on Robotics*, vol. 27, no. 2, pp. 346–359, 2011, doi: 10.1109/TRO.2010.2098623.

[17] Y. Li and Q. Xu, "Design and development of a medical parallel robot for cardiopulmonary resuscitation," *IEEE/ASME Transactions on Mechatronics*, vol. 12, no. 3, pp. 265–273, Jun. 2007, doi: 10.1109/TMECH.2007.897257.

[18] Y. D. Patel and P. M. George, "Parallel manipulators applications—a Survey," *Modern Mechanical Engineering*, vol. 02, no. 03, pp. 57–64, 2012, doi: 10.4236/mme.2012.23008.

[19] G. Yedukondalu, A. Srinath, and J. S. Kumar, "Structural analysis of delta parallel robot for cardio applications," International Journal, vol. 4, no. 2, 2011.

[20] L. Angel and J. Viola, "Fractional order PID for tracking control of a parallel robotic manipulator type delta," *ISA Transactions*, vol. 79, pp. 172–188, Aug. 2018, doi: 10.1016/j.isatra.2018.04.010.

[21] C. Liu, G. Cao, and Y. Qu, "Safety analysis via forward kinematics of delta parallel robot using machine learning," *Safety Science*, vol. 117, pp. 243–249, Aug. 2019, doi: 10.1016/j.ssci.2019.04.013.

[22] M. F. Chang, W. H. Mou, C. K. Liao, and L. C. Fu, "Design and implementation of an active robotic walker for Parkinson's patients," in *Proceedings of the SICE Annual Conference*, 2012, pp. 2068–2073.

[23] G. Renganathan, "Design and control of 3-DOF articulated robotic arm using LabVIEW and NI-myRIO," *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering*, vol. 3, p. 5, 2015.

[24] M. Farman, M. Al-Shaibah, Z. Aoraiath, and F. Jarrar, "Design of a three degrees of freedom robotic arm," *International Journal of Computer Applications*, vol. 179, no. 37, pp. 12–17, Apr. 2018, doi: 10.5120/ijca2018916848.

[25] K. Dusarlapudi, K. N. Raju, and V. S. K. Narayanam, "COVID-19 patient breathmonitoring and assessment withMEMS accelerometer-based DAQ-aMachine Learning Approach," *NVEO-natural volatiles & essential oils journal*, vol. 8, no. 5, pp. 1567–1575, 2021.

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