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Design of Robotic Manipulator for Space Applications

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Abstract

The paper illustrates the various design parameters implemented on our robotic manipulator that enables its usage in an alien environment and for space exploration. The robotic manipulator features a light weight variable configuration arm design, high precision actuating parts, a customized power distribution grids, tele-motion control system and an unorthodox approach for obtaining inverse kinematic values. The high configurability of this arm enables it to perform different tasks efficiently under a single platform. The 6 DOF freedom arm is custom designed to specific configurations in order to provide considerable advantage over conventional manipulators used in space applications. The arm is equipped with 2 types of end effectors in an adaptive manner such that it can be utilized in grasping both symmetric to asymmetric objects.

Keywords: Mars Rover, Robotic Manipulator; Space; Working Envelope; End Effector; Alien Environment

1. Introduction

Space exploration always comes with unknown variables and huge risks. From the dog Laika (First lifeform from earth to reach space) aboard the Sputnik 2 (Soviet Spacecraft) to engineering marvels like the International Space Station (ISS), it was understood that space exploration is limited by nature and technology and that space is inherently malignant for humans, but this never stopped us from exploring and finding answers to the mysteries that lurk within the skies. We have created machines that can go to places that were previously thought to be impossible. We had landed on Moon, mapped and studied various celestial bodies in our solar system and now are planning to colonize Mars and other celestial bodies. All of the technology that help us pioneer in realm of Space Exploration is derived from the integration of mainly 2 fundamental engineering sectors namely “Mechatronics” and “Robotics”.

CANADARM-Shuttle Remote Manipulator System (SRMS) [2] is a pioneering robotic work carried out by NASA and the Canadian Research Council (NRC) for the International Space Station (ISS). It was a 6-12 DOF configurable robotic manipulator developed to assist the astronauts in International Space Station (ISS) during the early days of its construction. It was a huge success which opened up a new domain for the use of robotic manipulators for space applications. The human arm is a versatile and agile component of the human body with over 23 DOF that enables us to perform our day to day life applications. Emulating the same concept in robotics can enable humans and machines to work together. The various extraterrestrial rovers that were sent to places like Mars are examples of the cutting-edge technologies that helped unravel some of the greatest mysteries of life and the universe. Mars rovers like the

Curiosity rover [4] and the Opportunity rover [5] uses different types of configurable robotic manipulators on board in-order to perform various scientific experiments.

This paper proposes the development of a 6 DOF manipulator made with advance composite materials and its application in interplanetary rovers proves to be having a greater advantage over conventional manipulators. The custom designed carbon fiber links offers high weight to strength ratio from within a light weight design. We have developed a custom made tele-control arm that enables the controller to physically feel the manipulator and control it remotely in order to perform precise manipulation tasks. Special power distribution boards are developed in order to efficiently distribute power and for recovery in the case of any damage. An unorthodox and efficient algorithm for Inverse Kinematics has been implemented in the arm for obtaining faster kinematic solutions. Reconfigurable prismatic links are provided which showcases a greater advantage when fitted over a mobile surface like a rover and it simplifies tasks such as opening bottle caps, refueling generators, picking up tools from ground etc.

The significant improvement in the design and the actuating parts gives it a maximum payload capacity of 3 kg. An improvised worm gear and a planetary reduction gear on the DC motor [3] provides a heavy torque to size ratio enabling the rover to tackle rough terrains wherein the arm can be used for repositioning the rover in case of toppling.

Section 2: – Mechanical structures, manufacturing methods and all of the important parameters of the manipulator such as design, payload capacity, working envelope etc.
Section 3: – Kinematic analysis and Structural Analysis
Section 4: – Control system and control algorithms.

2. Mechanical Structure

Some of the major improvements on the arm that makes it highly agile in space exploration are the light weight design, the usage of Aluminum 1060 alloy for the base and the connectors along with a carbon fiber shaft. This provides a compact and agile manipulator with high degree of articulation in all direction. This design also helps lower the CG (Center of Gravity) to a minimal lower level even when the arm is mounted over a rover. The detailed control flow pattern is depicted on Fig. 1.

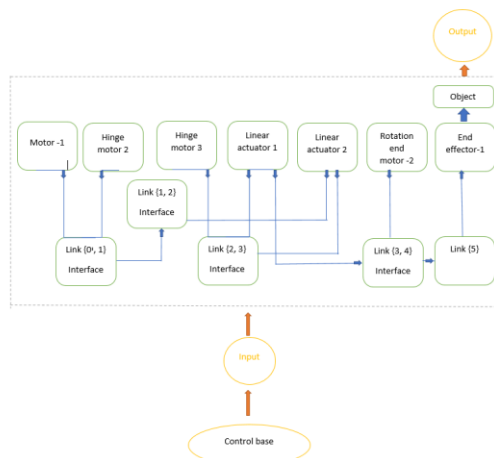

Fig. 1. Control flow pattern of mechanical system

The implementation of a linear actuator driven high load capacity prismatic link provides more working envelope enabling the manipulator to perform more complicated and intricate tasks. Encoders (Optical Encoder) of sensitivity 600 PPR and 560 CPR have been coupled with all the actuators in order to get precise rotational measurements allowing the manipulator to perform precise tasks starting from picking up stones and working on control panels to large tasks such as picking up tools, lifting heavy bodies etc.

The wiper motor (S15SWS1-12V) act as the primary motor at the base plate with a torque of around 52 NM, this allows the arm to lift a weight of over 120 Kg including the rover over which the arm is designed to be fitted. This ensures that in the case of toppling we could use the arm to reorient the rover to its normal attitude. The arm when not in use is designed to fold itself to form a Triangular configuration that shifts the CG downwards more providing better traction for the wheels thereby decreasing the chance of toppling. The arm is designed with 6 DOF (Including the end effector) but can be easily configured to a 7 DOF configuration with the addition of unit called “Cap holder” and a 15 mm stroke length linear actuator in place of “Load Distributer Bar”.

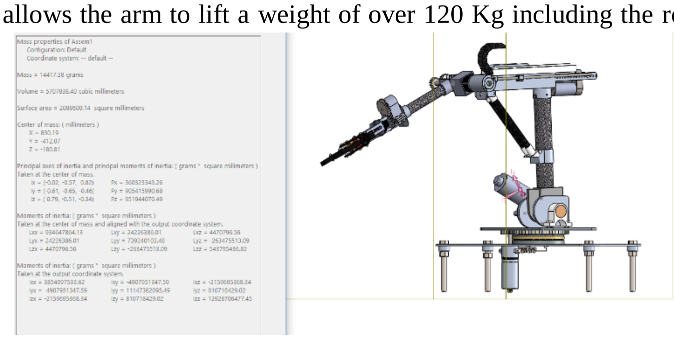

Fig. 2. Mass, CG and other data depiction via Computer

2.1. General Arm Arrangement

Unit 1 is the mount for the entire arm unit which holds unit 2, which is made of an Aluminum alloy and this holds the carbon fiber rods (OD-50, ID-46). The unit 1 meshes to a torque stabilized Wiper motor configured on a worm gear mechanism. This configuration helps in delivering a high torque with minimal power consumption.

Unit 2 is configured to be a prismatic joint whose motion is provided by a linear actuator that attached to the end of the carbon fiber rod with the help of an “Assisted-Base plate”. The linear actuator helps to change the overall length and configuration of the arm remotely, thus enabling it to reach longer.

This configuration extends the arm to a range of: -

Min circle - 800 mm

Max circle -1800 mm

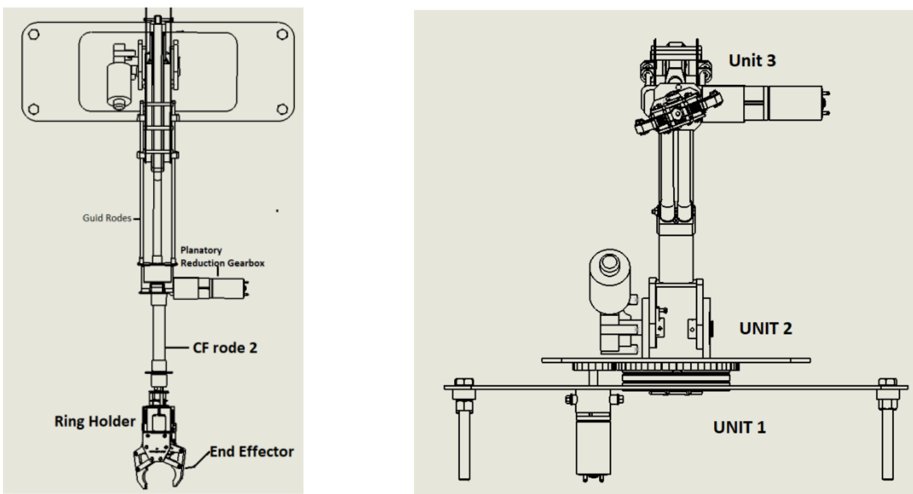

Fig. 3. Front View and Top view -part representation of arm

Unit 3 consists of a carbon fiber rod of diameter 20 mm and is driven by a motor of torque 300 kg/cm^2. The motor is configured with a speed reduction 3 stage planetary gearbox. Also, the specially designed mounting access of the motor enables reverse power transmission of the rotary motion (power transmission via motor mount rather than motor shaft) like that of a brushless motor. At the end of unit 3 is a 140 kg/cm^2 torque motor coupled with a reduction gearbox along with an inbuilt encoder. Its shaft is attached to a robotic gripper by a link named “Ring Holder” that keeps a slip-Ring inside for rotary power transmission over 360°. The gripper is a plastic SS based configuration that uses a worm wheel mechanism which is run by a DC 12 V motor. This ensures a Back-Gear lock mechanism along with a constant torque deliverance. The end effector tips are provided with Latex casings that ensures a damping effect while grasping delicate object such as electronic boards, fuses, bottles etc.

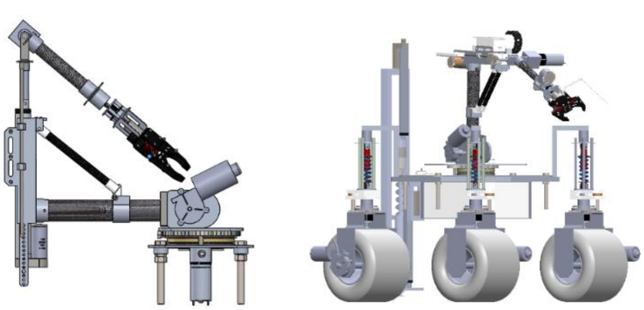

Fig. 4. Arm at Triangulated position to Lower Rover CG and Arm mounted on a Rover

2.2. Calculated Torque and Forces

The torque (T) required at each joint is calculated at the worst-case scenario (lifting weight at 90 degrees relatively), ensuring all units are consistent. For this arm, we have considered the torque required by providing the max torque of 150 Nm, calculated by software’s like the one in Fig. 5.

Along with it, 300 Nm Torque deliverance motors and 20 N force delivery linear actuators are provided. This provides the torque or force for the worst-case scenarios that the manipulator has to face, along with the pickup load weight of 2-4 kg. The arm has the capability to lift the entire rover in case of toppling, which is an important factor considering the unknown and difficult terrain that the rover may has to face.

L:	[cm]	M:	[kg]	A:	[kg]	T:	[kg cm]
L1:	10	M1:	0.4	A1:	0.3	T1:	5
L2:	4	M2:	0.4	A2:	0.2	T2:	9.400000000000002
L3:	30	M3:	0.5	A3:		T3:	55.900000000000006
L4:		M4:	0	A4:	0	T4:	0
L5:	300	M5:	0.5	A5:	0	T5:	670.9000000000001
L6:	0	M6:	0	A6:	0	T6:	0

Fig. 5. Torque on each links using the Torque Calculator Software

2.3. Payload

A payload can be defined as the maximum load carrying capacity of the manipulator. It is important to keep the payload in mind at the time of the arm's design and to check how much weight the arm can lift. The usage of heavy torque motors enables the arm to lift an overall weight of 3 Kg. High torque worm gear reduction gearbox motors that provide a torque of 150 Nm are used on the lower arm that not only maintains gear lock mechanism, but also helps to provide a constant torque to the arm without much power consumption. A planetary gear box (BB150) is used for the upper link's rotary motion which can deliver a torque of over 250 Nm. The RS 775 series heavy duty motor is used for rough usage near the stall limits.

2.3. *End-Effector*

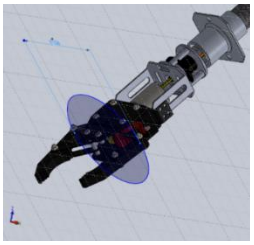

Fig. 6. End effector with its rotational

The end-effector (Fig. 6.) is 3D printed using ABS plastic to reduce weight, which also provides sufficient strength and surface hardness. A worm gear mechanism is implemented here, which is driven by a 12 V DC motor. Modules are made in such a way that it enables easy switching of the end effector for different tasks.

2.4. *Working Envelope*

Working Envelope is the maximum to minimum range that can be covered by the motion of manipulator. If we use the arm in all of the different possible directions (forward, backward, up and down) then a 3D map arises showing the working envelope. The arm's number of axis and DOF can manipulate the range of motion. Fig. 7. Below shows side view working envelope and top view working envelope of our arm. Here it is possible for the robotic arm to change its envelope according to the requirement. The specialized design that enables addition of an extra degree of freedom and linear variable link configuration offers a more extensive working envelope when compared to conventional robotic arm, which is essential in rough environment.

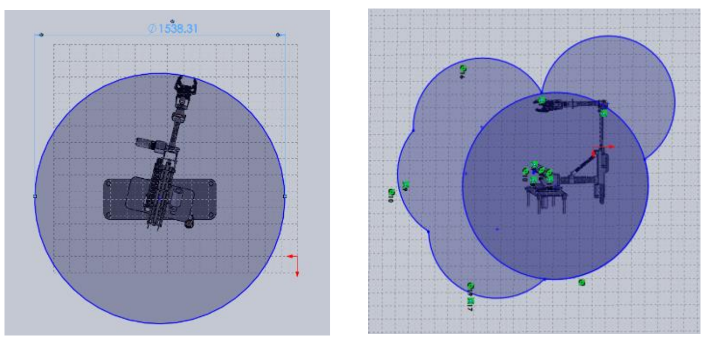

Fig. 7. Top view of arm with its x-plane maximum working space, Side view y –plane working space with on its maximum extended position.

3. Analysis of manipulator

3.1. *Kinematic Study*

Here, the manipulator composes of links which are affixed to each other via revolute or prismatic joints starting from the base frame to the end-effector. Calculating the orientation and position of the end-effector in terms of the joint variables is called as Forward kinematics. In order to calculate forward kinematics for this manipulator in a systematic manner, we use a suitable kinematics model. The Denavit-Hartenberg method which uses 4 parameters is the most common method for describing the robot kinematics.

These parameters are a_{i-1}, α_{i-1}, d_i and θ_i (angle) which are the link length, link twist, link offset and joint angle, respectively. A coordinate frame of reference is attached to each joint to determine Denavit-Hartenberg parameters.

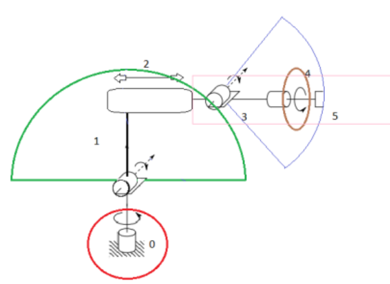

Fig. 8. Working envelope and kinematic movement representation

3.1.1. Free Body Diagram of Arm

θ_1 = Angle of rotation of base plate

θ_2 = Angle of rotation of link 1 respect to horizontal

θ_3 = 90° fixed joint with prismatic moment perpendicular to link 1

θ_4 = Angle of rotation of link 3 with respect to link 2

θ_5 = Angle of end effector rotation (link 5)

The equivalent line diagram of the robotic arm is used to compute the DH parameters for the different links of the arm. The parameters were tabulated and noted down systematically for computing the transformation matrix using the kinematics. The transformation matrix determines the orientation and the position of the end effector with respect to the reference coordinate system.

Table 1. Kinematic parameters

Angle	Link	Twist Angle	Link Length (cm)	Displacement	Cos α	Sin α
θ1	0	360°	500	0 cm	1	0
θ2	1	180°	30	0 cm	-1	0
θ3	2	0°	50 + 30	0 cm	1	0
θ4	3	60°	225	0 cm	0.5	0.5
θ5	5	360°	125	0 cm	1	0

The following figures show the reference and link coordinate systems of 6-DOF arm while using the first step of the animator. The values of the kinematic parameters are listed below in the table (I). Where lu, ls and lf are the link lengths of the shoulder, back arm and forearm respectively—

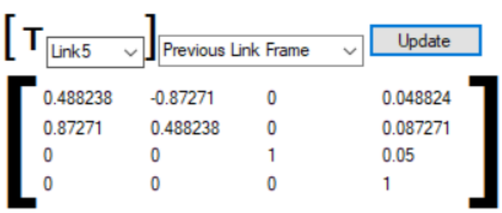

Fig. 9. End-Effector Kinematic parameters at fully extended position

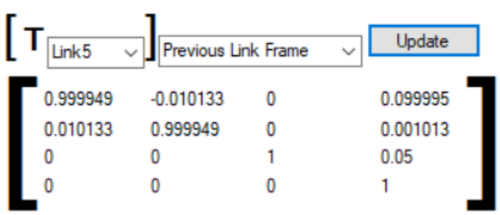

Fig. 10. End-Effector Kinematic parameters at all angles set to 45 degrees and stroke length set to half (150 mm)

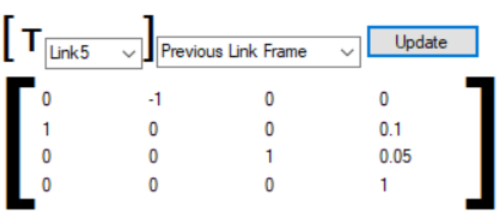

Fig. 11. End-Effector Kinematic parameters at Fully Retracted position

3.1.2. Kinematic graphical plotting using Robot-Analyzer

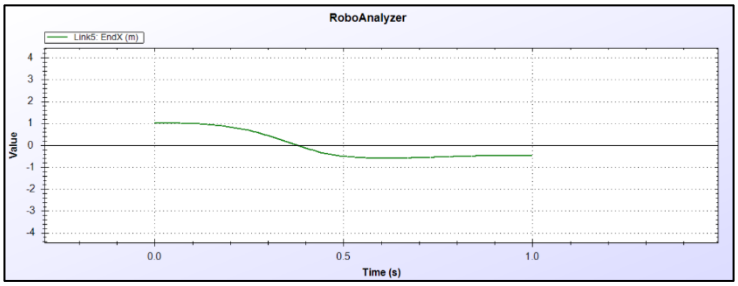

Fig. 12. Graph plot b/w End effector position relative to Previous links position over time

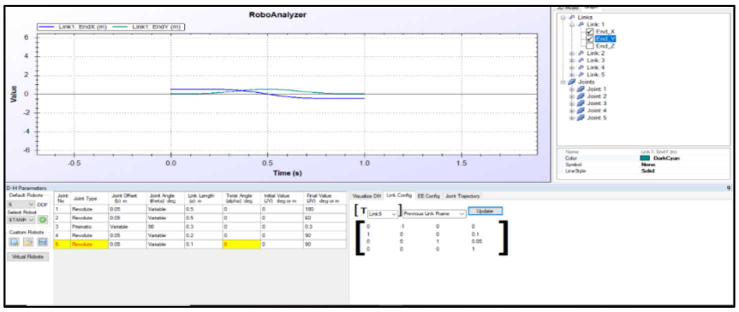

Fig. 13. Comparative plotting of X and Y coordinate movement of end effector along with DH matrix formation

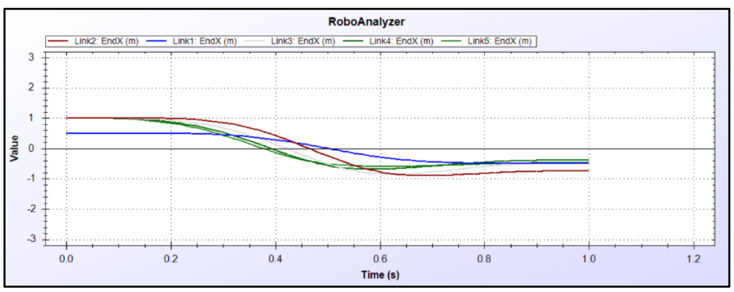

Fig. 14. Coordinate Relative motion of links with respect to time

3.2. Structural Analysis

The arm has been made of different materials ranging from Carbon fiber to Aluminum 1060 alloy as the structural and static analysis is critical for the design. We have used ANSYS and Solid works simulation for this purpose. The parts were discretized into individual units and the structural analysis was carried out using values higher than the numerically calculated values (approx. to material UTS).

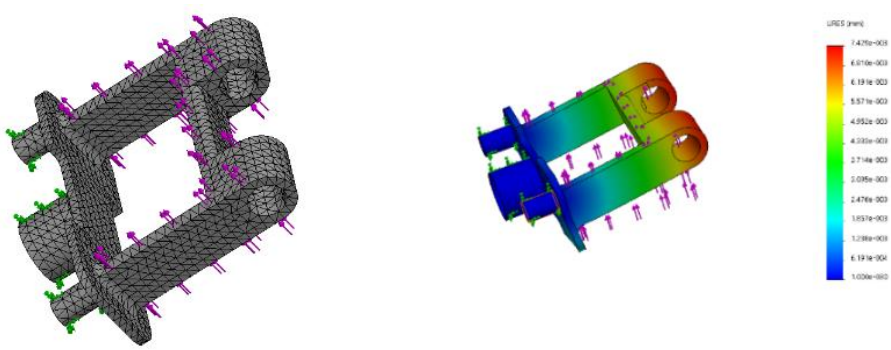

Fig. 15. Structural analysis, Stress formation on load

The above figure shows a connection mechanism that was custom designed for the arm. A static structural analysis of the body shows its deformation when a force of over 150 N was introduced on its ends.

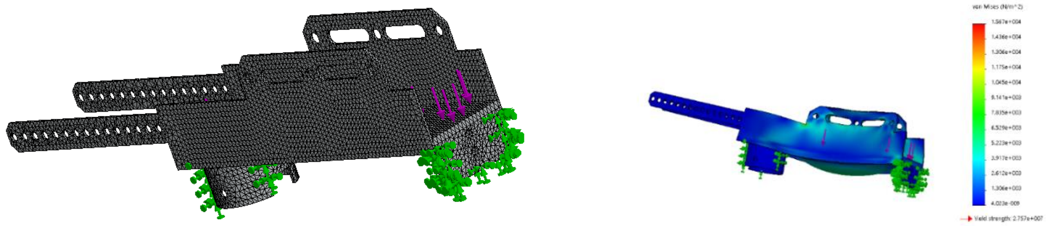

Fig. 16. Structural analysis, Strain and deformation on load

The linear actuator holder (figure 16) or static link is shown in the above diagram. Static structural analysis was carried out with the primary variables such as torsion and force which are taken in the worst-case scenarios. A factor of safety of 2.3 was provided to it.

4. Control System

4.1. Electronic Sub-System

4.1.1. Tele-operated Arm control

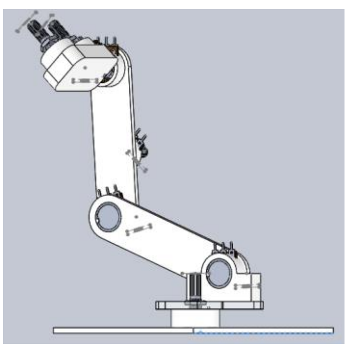

Fig. 17. Structural analysis, Strain and deformation on load

A tele-operated haptic arm (Figure 14) is used for manually controlling the main manipulator arm. We have established a two-way communication between the haptic arm and the main arm. Here, the data from the haptic arm is sent via 5 GHz Wi-Fi for operating the motors in the robotic arm. Similarly, the feedback from the main arm is sent back using the same wireless technology. This feedback is carefully analyzed and processed for improving the precision of movements and stability. The only thing we needed to identify and analyze was the angle made by the joints. For this purpose, we have used 10k Ohm rotary potentiometers, whose internal resistance varies with the angle turned by the knob from the pre-set position of zero. The potentiometer shows variations in voltage levels which in turn relates to internal resistance. A joint is commanded to move to a certain angle, and the voltage from the corresponding potentiometer is read. The data acquired from the potentiometers is now further carried over to an Atmel 2560 based microcontroller Arduino Mega for processing.

4.1.2. Sensors and Encoders

Quadrature encoders are non-contacted electro-mechanical sensors that use unique coded patterns to find real-time absolute angular position. They are considered as integral to any automation and precision controlling system. Due to their high accuracy and high resolution, they can be used in high-performance servo applications, precise position controlling of robotic arms, radar systems and various astronomical and avionic apparatus [6] [7] that require precise readings. The shaft of the encoder is coupled with DC geared motor to provide angular velocity. Each arm link is equipped with a quadrature rotary encoder used to provide precise angular readings that are read continuously to the host computer via the microcontroller. Force sensors are mounted between the joints of the manipulator. These sensors measure the amount of strain placed on each of these joints.

4.1.3. Drive System

The motor parameters were taken from the datasheet and were modelled in the system (figure 15). The speed was measured using a quadrature encoder working at 600 PPR (pulses per revolution) in accordance to the gear ratios of the gears attached to the shafts of the encoder and the motors. The pulses from encoder to measure position were read continuously in a 100ms interval and then divided by the time to get the RPM.

Every motor and actuating part in the arm has its own motor driver. BTS 7960 has been selected for driving the motors. The BTS 7960 is a high powered fully integrated high current motor driver which is capable of handling currents up to 43 Amps. Interfacing it to a microcontroller is made easy by an integrated driver IC that features logic level inputs, slew rate adjustment, diagnosis with current sense, dead time generation and protection against over temperature, overvoltage, under voltage, over current and short circuit. It is also protected against over temperature by an integrated temperature sensor.

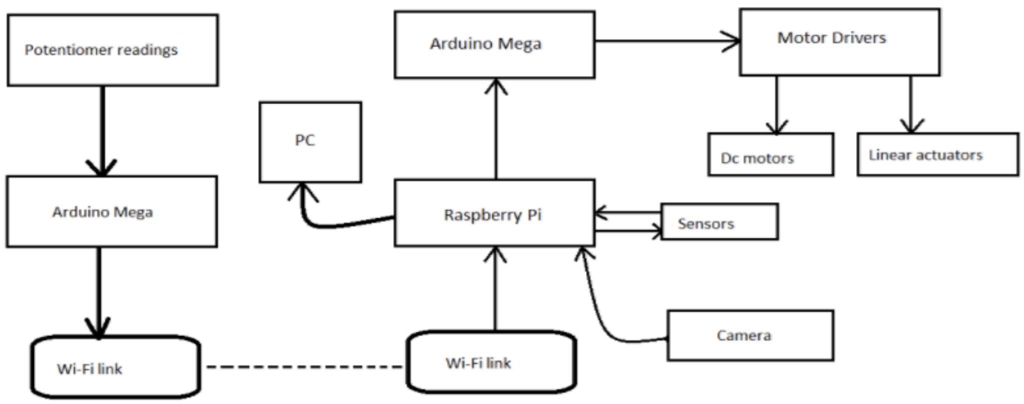

Fig. 18. Drive system control flow

4.1.4System Algorithm

Forward kinematics [8] [9] is the methods finding the coordinate position of the End Effector or your tool point or your tip of say an open chain system when provided with the angles of the various joints in the system. Whereas in Inverse kinematics the reverse happens, where we are provided with the coordinate position of the end effector and we have to solve for the angles of the joints. In most traditional approaches for Inverse kinematics, the problem is cast into a system of nonlinear equations or an optimization problem which can be solved using an iterative numerical algorithm. In order to solve an Inverse Kinematics problem, the processor has to perform a lot of heavy computations for solving all the complex Matrix and Partial Differential Problems involved in the traditional approach. For performing these operations, the system will need a lot of resources to process and as the number of degrees of freedom increase, the problem becomes more and more complex and hence would require more processing time thereby slowing the system down. Here we propose an Inverse Kinematics algorithm, designed for having a low processing time while maintaining a decent level of accuracy. Important features of the approach include:

- Completely Iterative approach where Solution for one joint is independent of the other joints besides the joint solved just before it.
- Besides the link with the end effector attached, all other link’s solutions are independent of the target position coordinates.
- The algorithm can be used for solving a problem with more than a thousand degrees of freedom to produce smooth and lifelike solutions accurately.

The current version focusses only on fully revolute joints with ‘n’ Degrees of Freedom. The whole setup is presented in a User-Friendly library structure with a set of simple functions that allow the user to setup a system using our approach within seconds without any background in the concept.

4.1.4. The Implementation

The system uses a recursive approach to reduce time complexity to O(n) rather than matrix operations. Matrix operations tend to have a time complexity of O(n3) however you can bring it down to O(n2.340) or lower with methods like [SUMMA] or [AP].

The algorithm takes in a vector representing the target position which then is subtracted with the current end effector position to get the change. The link is then pointed to (if revolute) or extended to (if prismatic) and moved to the appropriate location. The base position of the current link is then passed as target to the subsequent lower links recursively.

4.1.5. The Comparison

Simulations are performed in an HP 15 – AU118tx (Intel i7 quad core 2.9GHz processor, 8GB DDR3 Ram and 4GB NVidia GeForce 940MX GPU). All simulations are written in Python 3.6.8 with the same program backbone for getting the most accurate results as shown in Figure 16

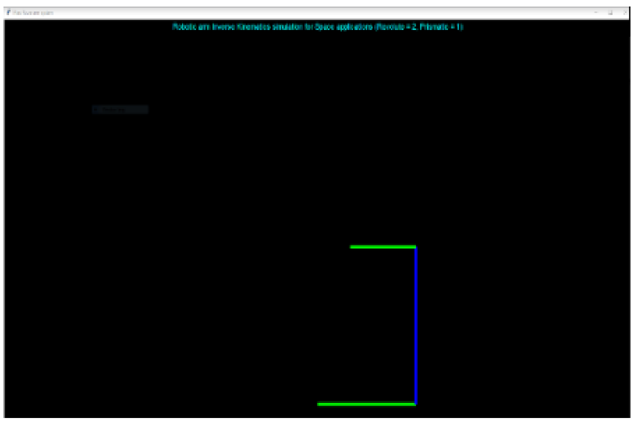

Fig. 18. Graphical kinematic joint emulation

4.1.6.Processing Timing

Table 2. Processing timings

Trial	Jacobian Method (m.sec)	Our Algorithm (m.sec)
1.	1.119910068682646	0.027856705108919716
2.	1.0543233958945561	0.025388389466357204
3.	1.1248466999677704	0.03279333639404472
4.	1.0056623160840383	0.022567457303428635
5.	1.0067201656451366	0.02186222426269651
6.	1.0402187350799135	0.021862224262696482
7.	1.2027749509686738	0.026798855547821496
8.	1.21017989789636	0.027856705108919695
9.	1.233805204760888	0.021862224262696454
10.	1.270829939399325	0.021509607742330433
Total:	11.269271374379308	0.25035772945991136
Average:	1.126927137437931	0.02503577294599114
Round:	1.1269	2.5036×10^{-2}

5.Conclusion

The space application robotic manipulator is an improvised new design that is specifically customized to meet the requirements of current rovers. It features a light weight design using composite materials such as carbon fiber and Aluminum (AA 5052). Manufacturing involves laser cutting of acrylic and waterjet cutting of Aluminum alloys in order to get a dimension accuracy of 0.1 mm. The arm is tested in various conditions and is proven to be effective not only in basic rudimentary tasks but also in complex ones. The arm has been showcased during ERC 2019 (European Rover Challenge 2019) aboard a rover in a simulative mars-like environment. The tele operated arm control helps to get a physical feel while controlling the arm unlike with a 2D joystick control. The customized power and electronic boards are made in a modular manner for easy user interface. The unorthodox and faster approach to inverse kinematics gave a faster response time for the arm. Study and analysis on the existing manipulator has been carried out and an optimized design was obtained. The final design is tested again experimentally using a fully functional prototype.

Acknowledgment

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