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Conceptual Design of a 7 Degrees of Freedom Robotic Manipulator for Martian Applications

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Abstract:
NASA and other space organisations are continuously working to create next generation Mars Rovers for the assistance of astronauts and explore the Martian surface. Rovers are required to explore mars and collect samples for further scientific analysis. To aid in this exploration the rovers must be equipped with a robust and agile robotic manipulator capable of working just like a human arm. This paper describes the design, function and control of a dextrous 7-DoF (Degrees of Freedom) Robotic manipulator. The working of the end-effector and wrist is also explained scrupulously. The manipulator developed to compete in the Indian Rover Design Challenge 2020 (IRDC 2020), was designed to cope with the adverse Martian conditions and still be able to perform a vast multitude of operations required to explore the alien planet. The arm is capable of performing complex operations like collecting soil samples by drilling onto the surface, operating switches and other electrical and electronic components, and assisting the astronauts during emergency situations.

Summary:
The paper conceptualises the design of 7 Degrees of Freedom Robotic Manipulator capable of working under Martian Environment.

Keywords:
Robotic Manipulator; 7 DoF; Inverse Kinematics; End-effector; Mars;

Abbreviations Used:

PH Stainless Steel - Precipitation Hardening
DoF - Degrees of Freedom
EP - Extreme Pressure
PFPE - Perfluoropolyether
PTFE - Polytetrafluoroethylene
FEA - Finite Element Analysis
PWM - Pulse Width Modulator
ADC - Analog to Digital Converter
SSI - Small Scale Integration
PID - Proportional Integral Derivative
FET - Field Effect Transistor

1. Introduction:

Planetary exploration and research is one of the most trending topics of the recent era. Various government and private organizations, including NASA, ESA, SpaceX, ISRO, CSA, etc. are performing aspiring science missions in order to explore planets like Mars with the aid of unmanned vehicles known as Rovers. Lessons learned through such expeditions play a crucial role in studying the planet in depth. This expedition is aided by the Robotic manipulator onboard the rover. This plays a crucial role in collecting samples for further analysis as well as carrying out repairs of the rover if and when required. The manipulator is capable of performing a myriad of tasks that help in the smooth working of the rover on Mars, and could also aid astronauts during emergency situations.

This paper presents the Design of 7 DoF Robotic Manipulator capable of performing all of these aforementioned operations under the harsh Martian environment. The manipulator is equipped with a self-swapping End-effector enabling the rover to perform all the tasks crucial for the success of the mission. Analysis of various components of the manipulator was carried out in-order to ensure its safety while operating on Mars.

2. Materials and Lubrication:

All the materials used for the design of the Robotic Manipulator were decided after optimization using various criterions like weight, hardness, yield strength, tensile stress, thermal coefficient, ease of machinability, etc. All the motors are enclosed in their gearboxes which have an internal layer of Silica Aerogel [1] for providing thermal insulation to the material. Furthermore, the motors are kept warm using heat from local RHU [2]. Parts are provided with gold-plating wherever they are required to be protected from radiation. A sensible choice of lubrication is of utmost importance. Owing to considerable research and studying various options, gear lubrication was insured by a mixture of 50 percent 802 EP grease and 50 percent 815Z oil to maintain the efficiency even at extremely low temperatures as this lubrication system does not dry out easily. Also, for lubricating other components such as bearings, motors, etc.; penzane-3 Pb Np oil and 601 EF formulated from PFPE oil and thickened from PTFE powder are used [3].

FEA conducted was done considering both temperature variation effects and loading conditions due to temperature and mechanical forces.

3. Mechanics:

The rover's arm is a 7 DoF dexterous articulated manipulator. It can provide serviceability at a position upto 2m above the ground and can lift objects upto 7kg. The arm consists of 5 rotary and 3 linear motors. The basic design is divided into 3 Sub-assemblies namely: Base, Limbs and End-effector. The design and analysis of these sub-assemblies is discussed below.

(A) Base:

The base of the arm provides a 360° rotation about the vertical axis and distributes the load of the arm and the payload over the rover chassis. The rotation of the arm is driven using a Worm-wheel mechanism reducing backlash and providing the arm with self-locking capabilities. The worm is driven using a Brushed

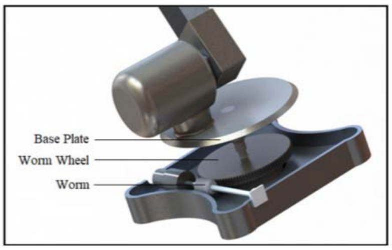

Figure 1: Base of the Manipulator

DC motor providing a torque of 100 Nm at 5 RPM. Double throated worm drive is employed for its high load capacity, better meshing, greater torque output and non-back drivability. Dynalloy 603 manganese bronze is chosen as gear material and steel for worm. Both the motor and worm gear are enclosed within an insulated aluminum housing to guard them from Mars' harsh environment.

The base would be resting upon a thrust bearing clamped at the rovers' chassis. The bearing allows smooth rotation of the arm over the chassis.

(B) Limb:

The limb sub-assembly includes shoulder and elbow links, two rotary motors for shoulder elevation and elbow joints, three linear actuators for providing pitch, and prismatic motions to the end effector, the motor for rotating the end effector, and the motor toggling the end-effector.

For smooth and efficient transmission of motion from the shaft of the motors to the links, Harmonic Drive Gears[4] based on the strain wave gear principle were chosen for the purpose as they offer advantages such as zero backlash, high transmission accuracy, compact design, high torsion stiffness and high torque to weight ratio over other gear reducers. An epoxy resin reinforced by the carbon-fiber is used as the composite as it guarantees minimization of stresses in dangerous cross-sections and an additional invariable stress distribution along the flexspline, which must be flexible in the radial direction but rigid in the torsion direction. Furthermore, for the wave generator and circular spline, 15-5 PH stainless steel is used.

Carbon fiber aluminum laminate [5] was chosen as the material for the design of the links due to its high fatigue resistance, strength, fracture toughness, impact resistance and energy absorbing capacity. This hybrid composite consists of thin layers of carbon fiber /epoxy prepreg sandwiched between aluminum sheets. AS4/3501-6 carbon fiber/epoxy prepreg and 2024-T3 aluminum alloy are opted for. The joints of links are aluminum parts which are connected to the links with Hysol epoxy 9460, which is recommended as the best bonding agent for carbon fiber to aluminum. Both shoulder and elbow links were driven using Brushless DC Motors having a torque of 40 Nm and 30 Nm respectively.

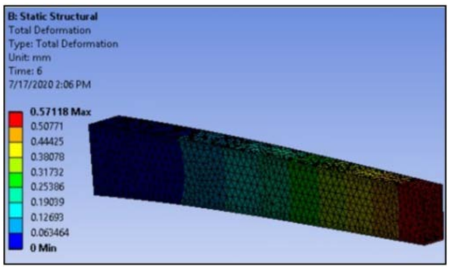

Figure 2: Deformation Analysis of Arm Links

In order to select the cross-sectional profile of the two links, circular and rectangular profiles were studied along with examining inclusion of 'X' or 'I' shaped support ribs or hollow tubes. Therefore, to get the most advantageous solution regarding the cross-section profile and dimensions, optimization of the cross-section has been carried out on MATLAB. For the optimization the objective function was the total deflection of the arm which included deflection of the links due to bending and twisting and deflection of wrist due to bending. Rectangular cross section with 'I' support was thereby chosen for the links due to the lower amount of deflection and greater stiffness in I-beam and lesser ratio of deformation to stress of rectangular one than circular cross-section.

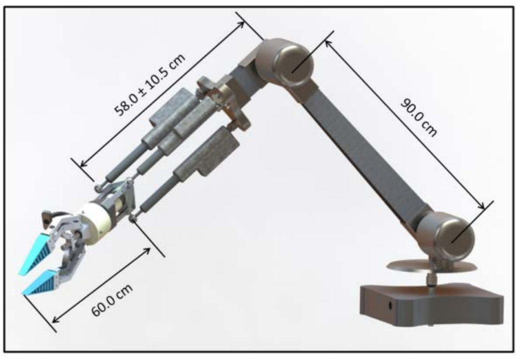

Figure 3: Dimensions of Manipulator

Final dimensions of the links were height = 70 mm, width = 35 mm and thickness = 3 mm. The link lengths were pre decided based on the desired reach of the manipulator to be 550 mm and 100 mm. The second link was kept shorter due to connection of three 47.5 cm linear actuators to it. Finite element analysis was performed for links with no taper and those with taper angles upto 1 degree. As a result, a negative taper angle of 1 degree was provided to the link in order to increase stiffness and strength of the links as tapering reduces deformation for the same stress.

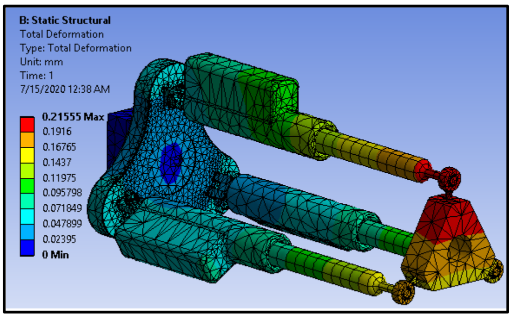

Figure 4: Analysis of Actuated System

The second link which connects the elbow motor to the wrist is a serial combination of Carbon-fibre aluminium laminate link and “The actuated system”. The carbon fibre aluminium laminate link is homologous to the above discussed link and served the purpose of connecting the actuated system. The actuated system is a system of 3 linear actuators connected in triangular fashion. The actuated system provides the wrist with 3 degrees of freedom of pitch, yaw and prismatic motion. The actuators are hinged on the base plate made of Aluminium alloy Al - 7079-T6(SN) which connects it to the above link. The actuators have a dynamic thrust of 1000N and a static load of 4000N with a stroke length of 21 cm. The coverings of the actuators are made of Titanium 6AL-4V and its lead screw is made of CA95400 aluminium bronze which enables the actuated system to withstand high radial and axial loads. The actuators are connected to the top plate via heim joints for facilitation of a 2 DoF joint. The ranges of both pitch and yaw motion are (-80 □ to +80□).

Prismatic motion of the end-effector is achieved when all 3 actuators open or close simultaneously. The pitch motion is achieved when L1 (Linear Actuator 1) is toggled in the opposite direction of L2 (Linear Actuator 2) and L3 (Linear Actuator 3) in equal magnitude. For the yaw motion, L1 is fixed whereas L2 and L3 toggle in the opposite directions having the same magnitude. From the aluminium top plate, another similar plate is suspended which holds the wrist motor enclosed in its gearbox. This motor provides axial rotation to the end-effector. The motor’s shaft is connected to another shaft which in turn is connected to another motor-box. This motor is for rotating multiple things like the gripper’s lead screw, the drill-bit, the screw-driver or the allen key. The upper portion of the motor-box has the motor and the subsequent gears. The lower portion of the motor-box facilitates the provision for autonomous swapping of the end-effector.

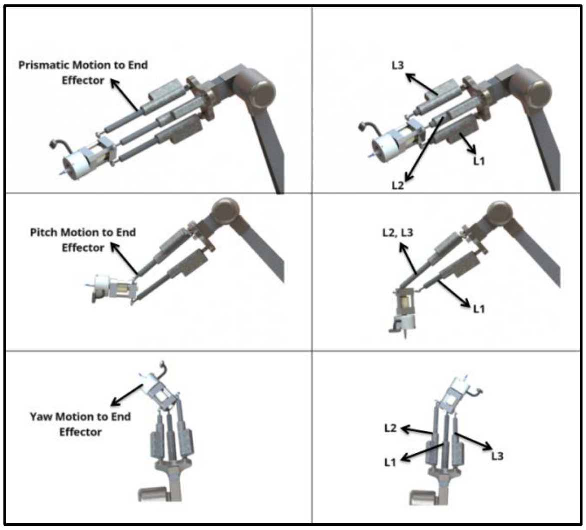

Figure 5: Actuated System

(C) End-Effector:

The end-effectors of the manipulator were designed to be easily swappable based on the operation that is to be performed. The end-effectors consisted of a primary general purpose gripper, a drill assembly, drill bits, screwdrivers and allen keys.

The primary gripper works on a linkage mechanism that transfers the vertical motion of the leadscrew to the horizontal motion of the claws [6]. The links and head of the gripper are made of HY80, HY-TUF alloy steel. The claws can grab an object upto 12 cm wide. The claws are designed to be shape-adaptive [7] in nature working on the principle of compliant mechanisms. For the claws, we have used vespel polyimide material over ordinary TPU (Thermoplastic Polyurethane) plastic. This has been done because its ductility and flexibility are maintained even at extremely low temperatures. This material has a lower thermal coefficient of expansion (CTE) than other plastics such as TPU and PTFE (Polytetrafluoroethylene). Also, graphite is added as a filler material (40% filled) to provide additional dimensional stability for mitigating the issue of CTE mismatch between plastic parts and mating metal components. Furthermore, it exhibits low friction and good wear performance.

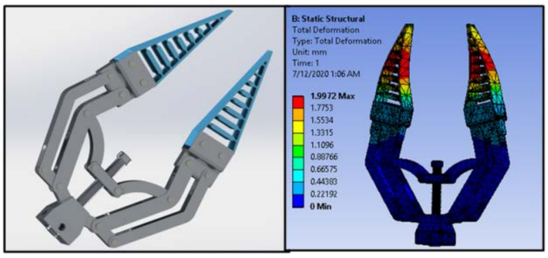

Figure 6: Design and Analysis of Gripper

FEA revealed that maximum deformation of approximately 2 mm is induced in the claws. Such large deformation value is a result of shape adaptive material used. However, a small value of stress is observed in these claws, lower than the yield stress of vespel polyimide.

The drill assembly consisted of a polycrystalline diamond Drill Bit and a Sample Filtration Unit (SFU). The drill bit was suitable for drilling through both hard and soft rocks. The cutting removal process was done using a hollow-stem auger system. The digging would be carried out by placing the second link of the robotic arm vertically, then the drill rotates and the drill is pushed by the three linear actuators. The SFU would filter the soil with the help of gravity and remove large particles that should not enter the Soil analysis equipment.

The End-effector would be controlled by a Brushless DC Motor providing a torque of 10 Nm at about 50 RPM.

4. End-Effector Swapping:

In order to facilitate autonomous swapping of the end-effector a novel solenoid based swapping mechanism was designed. The swapping plan has 2 sites of locking. Site 1 is the engravement on the lower surface of the motor-box. Site 2 is at the lower end of the shaft connected to the motor in the motor-box. At site 1, there are holes on the 4 surfaces as shown in the figure. The hole holds inside itself a solenoid which is connected to a titanium pin. The extruded engravement is designed such that the head fits right in. The 4 pins stay open, and are toggled inwards using the solenoids' actuation when the gripper's head is about to fit in. Once the head is completely in, the solenoids go back to their original state, thereby locking the head with the motor-box. At site 2, the solenoid is linked to the two pins using a spring. The locking mechanism is homologous to that explained for site1 wherein the shaft slots right in the lead screw. In the same way, the drill assembly can also be used as the end-effector wherein the sand container is analogous to the gripper's head and the drill bit to the lead screw.

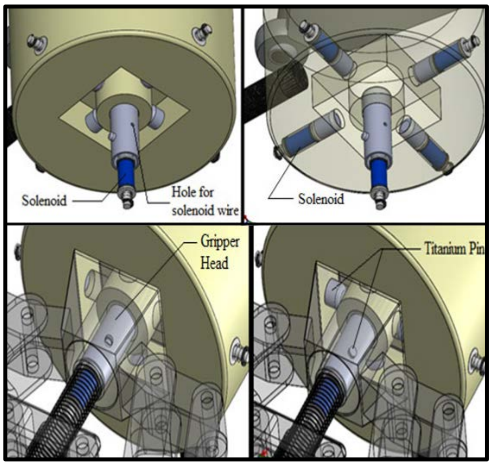

Figure 7: Swapping Mechanism

The swapping is carried out on the toolbox placed on the rover. The toolbox consists of slots for 1 gripper, 1 drill assembly, 2 spare drill-bits, 1 screw-driver and 1 allen key. The inner linings of the slots are made of Styrofoam to facilitate the allowances required for smooth insertions and removals.

5. Control Mechanism:

Specification	Base	Shoulder	Elbow	Wrist roll	Gripper Or drill
Type	Brushed DC Motor	Brushed DC Motor	Brushed DC Motor	Brushed DC Motor	Brushed DC Motor
Cont. Torque	100Nm	40Nm	30Nm	15Nm	10Nm
RPM	5rpm	10rpm	15rpm	30rpm	50rpm
Rating	24V	24V	24V	24V	24V

Table 1: Specifications of Motors Used

In order to provide a positional feedback a closed feedback loop is formed between the motors and the Microcontrollers. 12 Bit Absolute Positional Encoders working at 5V are used at every motor including the custom made linear actuators. With the help of internal PWM decoders the encoders provide an analog signal (0-5V) which is fed to analog Inputs of the MCU. Since the ADC present in the MCU has a resolution of 12 bit, we obtained the exact same value through a single signal line rather than using an SSI bus for the same. Thus this Analog input signal closes the feedback loop from the motors to the MCU. A PID controller running in the MCU is used to achieve accurate shaft positions and hence accurate positions of the end effector by implementing inverse kinematics.

The designed robotic arm can be modeled as a kinematically redundant manipulator [8] having a redundant degree of freedom at the wrist joint. Even though the Inverse calculation for the robotic arm designed, are complex, they are made faster by running the calculations on the CPU itself rather than the MCU. An extended Jacobian Technique [9] is used to achieve better obstacle avoidance, during drilling or accessing the tools on the rover, based on optimizing a distance criterion. Although analytical solutions are much faster than numerical solutions, in the case of robotic manipulators with more than 6 DOF no analytical solution exists. Also, since in optical encoders each position has a unique code, the arm orientations for swapping end effectors and transferring soil sample to the rover are stored in the CPU and therefore these orientations can be achieved with a single button without any new calculations, making the operation much faster.

Locking Mechanism: The swapping of various end effectors uses a locking mechanism based on push/pull solenoids. These solenoids are controlled directly by the MCU through a controller specifically designed for them. It uses Power FETs to provide monetarily high current required to push or pull the solenoids.

6. Materials and Methods :

The objective of this research was to design a 7 DoF Robotic Manipulator that was adept enough to work under the harsh Martian environment while performing the crucial tasks in order to analyse the geology and composition of the surface of Mars and aid astronauts during emergencies. The design process was initiated by drawing an under-defined sketch using solidworks and using it to optimize the design in order to maximize range while minimising the total length of links. Solidworks was then used to design and assemble various components and sub-assemblies of the robotic manipulator. The components were analysed for failures using ANSYS Workbench , a minimum factor of safety of 2 was ensured for each individual component, hence making our design reliable.

7. Conclusion:

Through this paper we presented a design of a 7 DoF Robotic manipulator capable of operating under harsh Martian Environment. The manipulator designed would be adept to perform all the tasks in order to successfully explore the alien planet as well as aid astronauts during emergency situations. Inverse kinematics was used during the design process this not only increases the precision but also increases the autonomous capabilities of the manipulator making it a lot more suitable for applications in remote locations where maintaining a constant communication link is not possible. The end-effector of the arm was designed as separate modules that could be readily swapped autonomously based on the needs.

8. Future Scope:

1. For Space Exploration Applications: It has a tremendous potential for application on Extraterrestrial Surface for assisting astronauts and performing crucial sample collection tasks autonomously.

2. Manufacturing: The applications of the arm could further be extended to various manufacturing lines wherein, the precise motion of the manipulator lets open a wide field in various processes including welding, painting and transporting.

3. Exploring hazardous areas: The arm could be mounted on robots that may explore areas inaccessible and unsafe for human exploration, such as electric grids, deep mines or radiation exposed areas.

4. Agriculture: The arm could be utilized to collect soil samples from various parts of the field, which can further analyzed for agricultural research

5. Medical: The arm could be used for collecting various medical specimens such as nasal and oral swabs hence limiting human contact and reducing the spread of diseases.

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