Exploration and Selection of a Robotic Manipulator for Space Applications

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The purpose of this study is to explore modern robotic arm platforms with intent to design and deploy one on a 1U Cubesat. The scope of this paper is broad and aims to uncover practical uses for small robotic systems in space. While structure and physical design are important topics of discussion, ideas of actuation and control will also be looked at. This paper aims to define a realistic path for designing and manufacturing a robotic manipulator. While complex systems are considered, this is contrasted against the likelihood of creating a final product. Taking all factors into consideration, a mission and design for s robotic arm is proposed.

I. Nomenclature

R = revolute joint
P = prismatic joint
S = spherical joint
EVA = extravehicular activity
DOF = degree(s) of freedom
end effector = device at the end of robotic arm
workspace = locations reached by end effector

II. Introduction

Space systems pose various challenges over the course of operation. From structures needing assembly (ie the ISS) to maintenance of existing craft (ie Hubble Space Telescope), there is an inescapable need for in-operation manipulation. This has historically been accomplished by a handful of methods such as human space flight, creative actuation, and robotic arms. While EVA missions are dangerous and costly, there is a large advantage to having human dexterity as a tool. It allows for a multi use role as opposed to single use actuation (ie telescoping boom). This dexterity can also be attained via robotic manipulation.

Robotics has seen a large amount of use over the last couple decades and offers solutions to a wide variety of problems. Robotic systems contain a feature known as reprogrammability. This allows them to extend past a single use case. A system like this is beneficial for an environment like space, which is inherently dangerous for humans. Having a system that can fulfill multiple roles and alleviate the need for EVA is ideall. This drives a need for the development of a light weight robotic manipulator.

III. Methodology

Control traditionally falls into two different categories: open-loop and closed-loop. Open loop control requires input. The system has no knowledge of previous or future states. A simple example of this would be a toaster.

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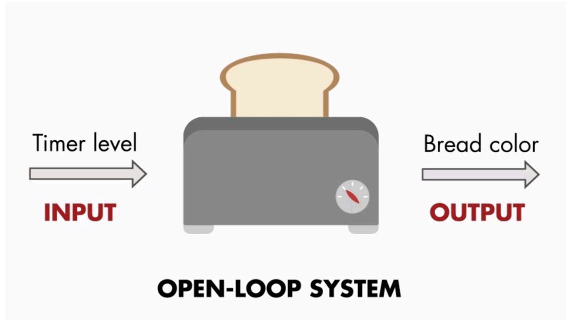

Fig 1. Open-loop system example[1]

Open loop control has been used in robotics (known as non servo robotics) relying on physical stops or an operator. Systems like this will not be considered for obvious reasons.

Modern robots considered here fall into the category of servo robots[2] and implement a closed loop control system. Examples of these robotic manipulators can be in industrial, aquatic, and space applications. The use of motors and encoders (as well as other sensor input) allow for precise control and state determination. An example of this would be the KUKA 500 FORTEC pictured below.

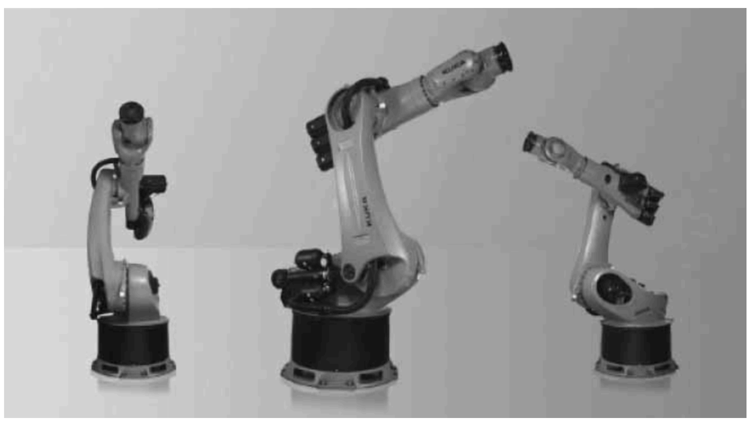

Fig 2. Industrial manipulator[2]

Among these robotic manipulators, there are common robotic joints that allow locomotion. The most common being prismatic (P), revolute (R), and spherical (S). These definitions are important in order to understand how a robotic manipulator moves. Pictured below is the P and R joint.

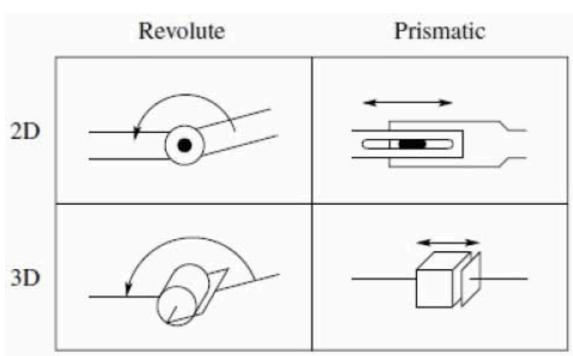

Fig 3. Common robotic joints[2]

With these baseline definitions, advanced systems can be reduced down their basic actuation mechanisms.

IV. Results/Findings

When exploring examples of robotic manipulators used in space, the most famous example is the Canadarm. This system uses 6-7 DOF (different iterations had different configurations) and achieves locomotion through 2-3 shoulder joints, 1 elbow joint, and 3 wrist joints[4].

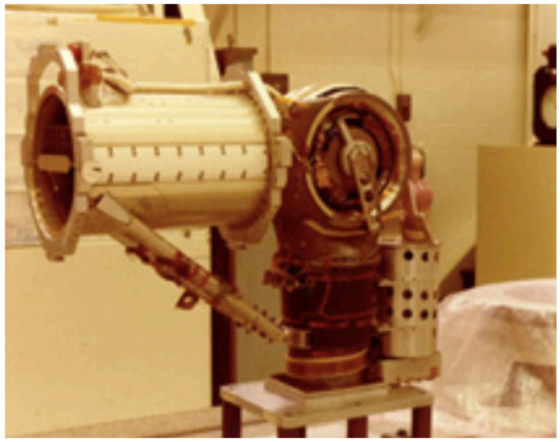

Fig 4. Canadarm P joint

While this system is out of scope for this project, it does draw into consideration some important design characteristics. The extensive use of R joints allude to the efficiency of the R joint over a P joint. In fact, a R joint can cover the same distance as a larger P joint[2]. For a robot system deployed on a cube satellite, size and mass is a large constraint. Joint selection can play a large role in final product size. Furthermore, microgravity alleviates some of the weight considerations of the payload. This allows for a weaker/smaller joint when compared to a robotic manipulator subjected to gravity. This contrast (microgravity vs gravity) is also shown in the Candarm's electrical power consumption. Canadarm was capable of lifting 30000kg in microgravity with "less electricity than a tea kettle"[3]. Canadarm also implemented cameras, which will be a necessity for a remotely operated robotic system.

Scaling down to a more approachable design (yet still too large for this application) is the TAGSAM (touch and go sample acquisition mechanism) arm used on the OSIRIS-REx craft. It is used for sample retrieval. This arm appears to use three R joints to control the end effectors location within a single plane. The DOF is limited as the mission did not call for motion outside one plane. Pictured below is the extended arm which showcases the use of R joints in the structure.

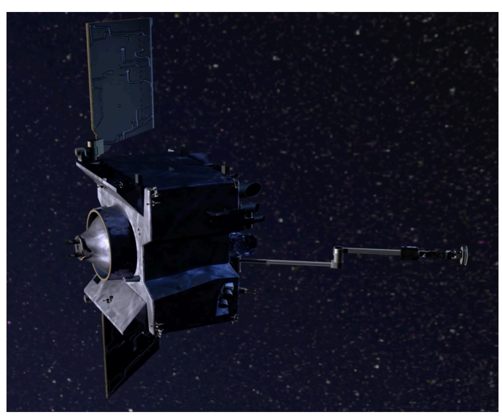

Fig 5. Still image from TAGSAM arm animation[5]

The simple design of this arm is a quality that should be implemented into this project's design (cubesat robotic arm). Added complexity must be avoided for a team not well versed with robotics. The design, however, is limited in terms of workspace. TAGSAM does also implement a highly specialized end effector[6]. Although this particular mechanism is not viable, it does show that a unique end effector can be developed if the mission calls for it.

A cube satellite solution for in-space assembly was created by a research team from Arizona state university. This arm uses 6 DOF and computer vision to track objects with the goal of autonomous control. The arm features a relatively simple design with what appears to be a kinematic chain of R joints. This is pictured below.

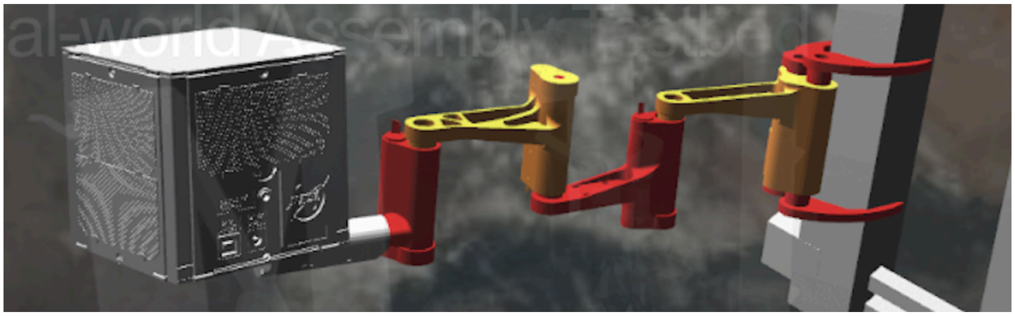

Fig 6. Autonomous cube satellite arm[7]

This was tested using hardware in the loop, but does not appear to have been deployed. It is a bulky design and it requires a large amount of storage. The end effector does feature a design and would be easy to implement. It is a simple actuation mechanism and is built to grab long slender objects. The complexity of this system comes in its method of control, one that I believe is out of scope for the research project.

The aquatic environment is an area that has a lot of innovation for robotic manipulation. Aquatic robots can be used for a variety of applications from maintenance to sample collection. While exploring current systems on the market, it is obvious that most systems would be overengineered for a cube satellite (underwater robots make use of the fluid they operate for certain advantages which is not possible in a vacuum). The arm pictured below was created by HDT and features a minimalist design that would be possible to replicate and useful for space applications.

Fig 7. HDT aquatic arm[8]

This uses a series of R joints with the last joint (before the end effector) having an axis of rotation perpendicular to the previous joint. This gives control over the orientation of the end effector. The downside to this arm is that it is limited to operation in a single plane. This constricts the workspace and would require rotation of the spacecraft for any out of plane object. This could pose a very difficult controls problem.

The last robotic system explored was prototyped by the Naval Academy and purpose built for a small satellite. It was created for maintenance and assembly. This is a promising system as it is close in scope and design to a system that could be built in this research project. The arms are pictured below.

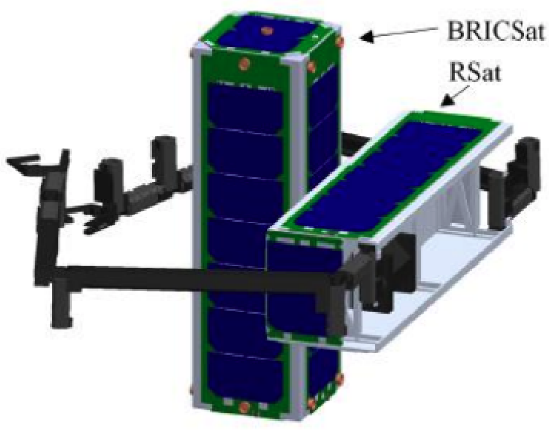

Fig 8. Naval Academy two arm[9]

This two arm system uses a camera to aid in operation and end effector alignment. It is difficult to see what axis of rotation each joint uses. The arms have the capability to hand off parts between end effectors. Two modules are used in this configuration, one that contains the arms and another that contributes propulsion. It uses clamp end effectors with a camera on the end of the arm. The use of two arms gives the system a larger workspace but does present more complexity in terms of controls.

V. Discussion

As seen above, a robotic manipulator in space has several applications. This varies from assembly to maintenance to sample retrieval. The topic of assembly and maintenance appears to be the most popular as there were several projects devoted to this. Because there are various uses for a robotic arm in space, I would like to see a multi-role module that could be used for all of the above. Instead of a mission driven system, the arm can be portable. The first iteration of the robotic arm will have to be remotely controlled as developing a fully autonomous system is out of scope for this project. I believe a single arm should be developed first with possibility for a second.

I personally would like to see this independent study focus on the issue of orbital debris. A cubesat equipped with a robotic arm and propulsion system could either collect small pieces of debris, or attach to medium sized debris and deorbit it faster. This could help tackle the idea of sustainable space and the ever growing problem of space junk. This issue was introduced in both of the orbits classes I took and is only getting worse. There are dead space craft, rocket bodies, and pieces of space craft littering LEO which is making space access more difficult. Developing a system that can contribute to cleaning up space would benefit the entire planet.

Even with a goal of reducing orbital debris, I would like to emphasize the idea of modularity of the system. This way it can be deployed on a cubesat or another small satellite. This will extend its usage past a single mission.

For this independent study, I believe the level of complexity chosen will dictate whether or not a final product is created. Ambition is good but can result in an unachievable goal (this was evident in past projects). For aerospace students with limited knowledge in the field of robotic actuation, control, and system design, the less complexity the better. I am proposing a simple kinematic chain of R joints (3-4), primarily with parallel axes of rotation (for the shoulder and elbow joint). The end effector would use a R joint inline with the arm for orientation control and utilize a clamp. This system would end up looking similar to the HDT arm. It would be relatively simple to control (compared to other systems). A robotic controller would have to be developed. It will be packaged up in a self contained module with hardware and software interfaces. It will feature a camera for object detection and to allow an operator to see what the cubesat is seeing. Open source projects, like ROS and OpenCV, should be utilized to reduce workload and increase performance.

For testing purposes, a network protocol can be implemented to send data to and from the robot controller. This can be done by giving the robot controller wifi capabilities and testing on a local network (2.4 or 5 GHz). A custom protocol built on TCP/IP can be developed, or an existing application layer protocol like MQTT. This process will mimic how the arm is used in orbit, without the need for sophisticated communications equipment. Live video from the camera can be streamed to another computer using OpenCv and a socket connection (most likely TCP/IP). This will make localized testing of the arm simple.

While the proposed design limits the manipulator to a single plane (2D workspace), this design is achievable with the timeframe and budget we have. Extending the workspace to three dimensions is obviously more useful but much more complex. I would like to see the first iteration feature a more conservative approach with room to grow in further projects.

VI. Conclusion

While the system proposed above is not as extravagant as some of the commercial robotic manipulators, it does strike a balance in operational capability and what is achievable with a small group of undergraduate aerospace engineers. It offers enough capability to satisfy the proposed mission and can be built upon in the future. With an emphasis on small size and portability, it could even see use on systems like a rover (with some attention to structural constraints). This project will provide a challenge and require a lot of extracurricular study (the aerospace program does not exactly teach you how to build and control a robot). The proposed arm design is feasible and will result in a useful system with a variety of applications.

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