University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Conceptual Design Document (CDD)
Remote Intra-Vehicular Robotics (RIVeR)

Monday 28th September, 2020

1 Information

1.1 Project Customers

Name:	Loren McDaniel
Email:	loren.mcdaniel@sncorp.com

1.2 Team Members

Project Manager: Kyle Li Email: kyli8681@colorado.edu Phone: 720-275-2127	Lead Systems Engineer: Lindsay Cobb Email: lindsay.cobb@colorado.edu Phone: (415) 450-7535
Name: Logan Vangyia Email: lova2860@colorado.edu Phone: 314-691-8445 Position: Translator Lead	Name: Nicholas Miller Email: nimi1223@colorado.edu Phone: 973-903-9779 Position: End Effector Lead
Name: Marin Grgas Email: magr4013@colorado.com Phone: 310-779-9322 Position: Structures/Manufacturing Lead	Name: James Tiver Email: Jati6685@colorado.edu Phone: 970-213-6307 Position: Software Lead
Name: Jordan Abell Email: joab9590@colorado.edu Phone: (303) 887-9295 Position: Software/Dynamics Lead	Name: Bruce Barnstable Email: brba0083@colorado.edu Phone: 720-877-1437 Position: Safety Lead
Name: Jett Moore Email: jemo0269@colorado.edu Phone: 303-990-2507 Position: Electrical Lead	Name: Brandon Torczynski Email: brto2556@colorado.edu Phone: 808-308-3630 Position: Testing Lead
Name: Alex Ferguson Email: alfe2986@colorado.edu Phone: 724-393-7211 Position: Finance Lead	Name: Peter Amorese Email: peam6502@colorado.edu Phone: 720-456-9880 Position: Robotic Arm Lead

Contents

2 Project Description

Project RIVeR will design and manufacture a component of an intra-vehicular robotic (IVR) system that is be capable of moving cargo from an exterior hatch to designated storage areas aboard the Sierra Nevada Corporation LIFE module. The group will focus on demonstrating the robotic manipulator's ability to orient and translate a cargo bag. Due to the proof-of-concept nature of this project there is no expectation of flight-ready hardware. This is the first element of what will eventually be a multi-step system to completely unload and stow cargo within the LIFE module. A high level integration plan will be provided to the customer for development beyond the IVR system designed here. This will help guide future IVR systems that will be responsible for transporting cargo through the different levels of the habitat and a storage solution.

RIVeR will integrate a robotic arm with a translation system that is capable of grasping a cargo bag and moving it through the core of the LIFE module. This will be achieved through a remote operator in combination with the ability to implement semi-autonomy*. The robotic system will have the ability to rotate and translate cargo bags in a zero gravity environment. This may include interacting with mock-ups of docking hatches and pathways. The robotic arm will have an end effector to capture and hold bags during transportation. The end effector will have multi-functionality per NASA requirements. The system will be outfitted with a sensor suite that will determine the location of the robot within its environment and the position of the bags. A decision-making protocol, whether autonomous or through an operator, will be implemented to determine completion status of a task.

2.1 Concept of Operation

The concept of operation for RIVeR outlines the steps to retrieve a bag from the cargo hatch and deliver it to a drop off location. This will include rotating and translating the bag once it is in control of the robotic arm.

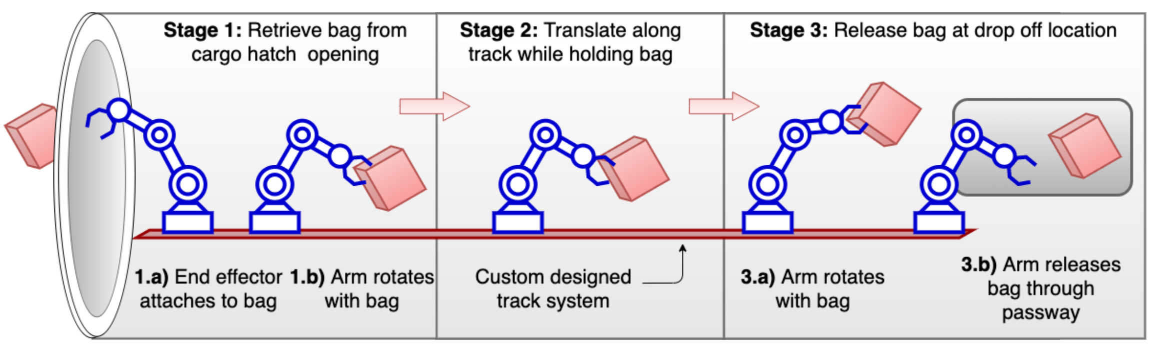


Figure 1: ConOps

Please note that the robotic arm, end effector, and translator are not final design solutions, they are just a functional description. The final design selection is detailed in Section 6.

*A combination of a decision making software and automated processes pre-programmed into the system

2.2 Functional Block Diagram

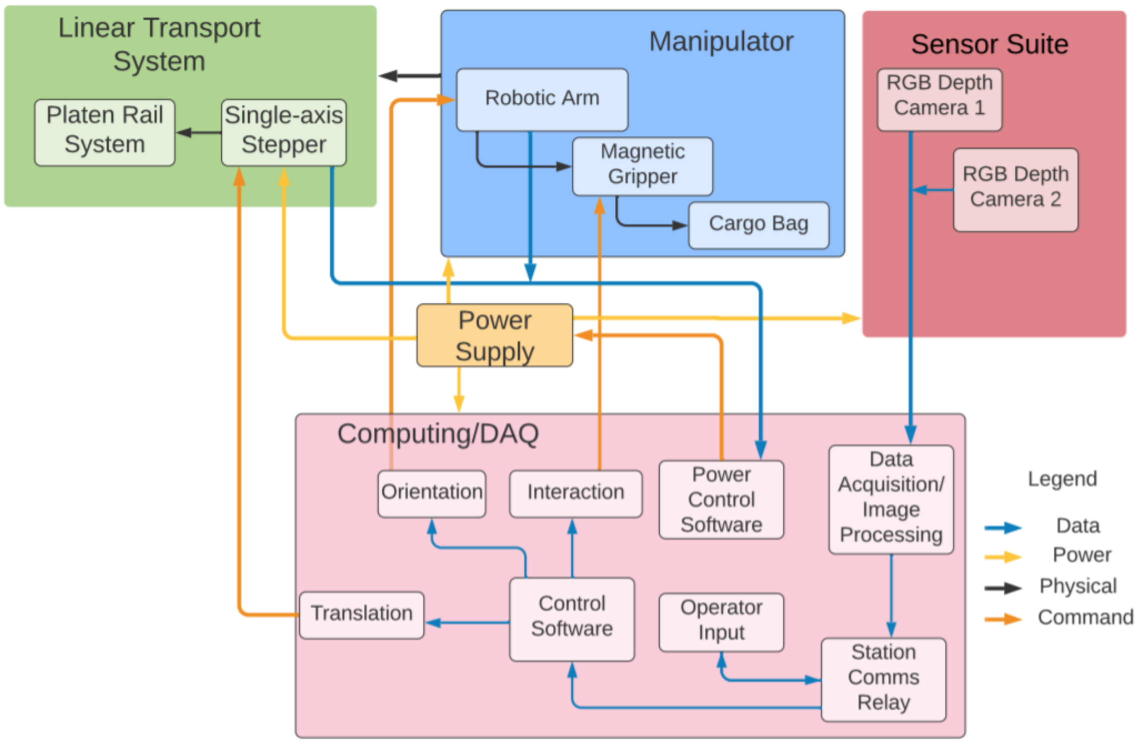


Figure 2: Functional Block Diagram

2.3 Levels of Success

Level	**Translator**	**Robotic Arm**	**End Effector**
Level 1	Design a platform that is capable of being mounted to the rail dimensions provided by SNC.(Trade Study)	Robotic arm can move to a desired pose under a given command without colliding with environment (Mock-up of LIFE module core based on provided CAD file)	End effector is able to take a command to operate the bag capture mechanism.(Trade Study)
Level 2	Ensure translator is able to integrate with the robotic arm including power and communication system.	Robotic arm can plan and move to a specified pose while the base is being moved by the translator.	End effector is able to capture bag with human input and maintain hold for the duration of translation.
Level 3	Translate robotic arm up to 2.5 meters in one direction given a control input with 5 cm of accuracy. (Track length based on customer spec)	Robotic system can secure a bag and release it at a specified location, with a remote operator determining what bag and drop off location.	End effector is able to align itself, grasp the bag, and control the bag without user input.
Level 4	Translation is automated and repeatable; sensor suite returns position and velocity data to the system/user to refine position during operations.	The system will complete a cargo transportation task by identifying, locating, securing, and releasing a bag with no manual input besides final location.	End effector is able to identify bags by cargo classification.

2.4 Functional Requirements

FR.1	The system shall be capable of translating a 5kg cargo bag the length of the track.
FR.2	The system shall be designed to only utilize a maximum of TBD at any time during operation.
FR.3	All systems shall be operational in a 1G testing environment
FR.4	The end effector must be interchangeable depending on the given task.
FR.5	The translation system shall be able to navigate from one end of the track to the other.
FR.6	The end effector shall be able to control and direct cargo.
FR.7	The system shall be able to either autonomously decide, or give the operator the means to decide, if the given task has been completed or failed beyond recovery.
FR.8	The linear translator shall be able to maintain structural integrity under the torques and forces applied to it when moving cargo.
FR.9	The system shall operate within the volume of the core.

3 Design Requirements

The design requirements are flowed down from the functional requirements. The set values are based on costumer requirements, industry standards, and anticipated capabilities of the system. The verification is listed as *test*, *observation* (measurement), or *analysis* based on how the requirement will be verified.

FR 1: The system shall be capable of translating a 5kg cargo bag the length of the track.

- *Motivation*: The system shall be able to transport cargo bags of variable mass with a maximum of 5 kg. The value of 5 kg is the average mass of the smallest CTB (Cargo Transfer Bag) bag as specified by NASA [2].
- *Verification*: Demonstrate the system can carry the desired weight and volume.
- *Validation*: The ability for the system to carry varied masses/volumes will enable this system to be applicable to the transportation of cargo for most cases within the LIFE module.

DR 1.1: The translation system shall be able to accelerate the cargo bag and combined arm/end effector 3 cm/s^2.

- *Motivation*: A minimum acceleration ensures robotics operations will occur in a reasonable time frame of 1.5 min. Since the habitat will be uncrewed, there is time constraint, it just needs to be reasonable. The force required to move the system will be greater in a 1G testing environment. If the velocity of the system is 3 cm/s, then the whole translation will be 1.5 min. The anticipated force available is >30N but even with 20N the system can support 667 kg which is far greater than expected.

$$t = \frac{d}{v} = \frac{2.5m}{0.03\frac{m}{s}} = 90s \tag{1}$$

$$m = \frac{F}{a} = \frac{20N}{0.03m/s^2} = 667kg \tag{2}$$

- *Verification*: **Test**
  Demonstrate the translation system acceleration with the required mass attached. Record acceleration with on-board sensors.

DR 1.2: The end effector of the arm shall be able to maintain security of bags with a force greater than or equal to 80 N.

- *Motivation*: The end effector must be able to lift the 5 kg bag in 1G. To account for slight acceleration from the arm and translation system, the requirement ensures there is a 30N margin once the bag is captures.

$$F = (m * g) + margin = (5kg * 10m/s^2) + 30N \tag{3}$$

- *Verification*: **Test**
  The end effector shall be attached to a force gauge that will be pulled to exert a force of 80 N.

DR 1.3: The length of the track shall be 2.5 m.

- *Motivation*: The total length of the LIFE module core is approximately 5 meters. The system is expected to traverse half of the core.
- *Verification*: **Observation**
  It will be designed and measured to this specification.

FR 2: The system shall be designed to only utilize a maximum of TBD at any time during operation.

- *Motivation*: The customer specifically did not provide a power constraint because it is not expected to be flight quality. Once design choices have been selected a model can be made to estimate power consumption. The model will drive the limits of the power budget. The final flight-ready system will have a power budget of 500W but that is not expected for this project.
- *Verification*: During operations, the power draw will be monitored through sub-system level testing and full system integration.
- *Validation*: The system will need a power budget to protect the operating conditions of the hardware.

DR 2.1: All sub-systems shall operate within a TBD W power limit.

- *Motivation*: Once the power draw has been modeled, each subsystem will be allocated its own power budget.
- *Verification*: **Test**
  The power draw of each subsystem will be tested prior to full system integration.

FR 3: All systems shall be operational in a 1G testing environment

- *Motivation*: Although the system will eventually be implemented in a micro gravity environment, the only way to validate the system is in 1G. Therefore all elements in the system must be operable in a 1G testing environment.
- *Verification*: Demonstrating the system in 1G environment.
- *Validation*: SNC has specified a particular focus on demonstrating cargo transportation and handling, since demonstrating in a zero-G environment terrestrially will be extremely difficult, testing in a 1G environment is suitable.

DR 3.1: The translation system shall be able to support the robotic arm and end effector in 1G.

- *Motivation*: The platform for translation will need to support the weight of these components in 1G.
- *Verification*: **Observation**
  Place equivalent weight to robotic arm on translation platform.

DR 3.2: The translation system shall be capable of translating the robotic arm, end effector,and cargo bag's combined mass.

- *Motivation*: The translation system must be capable of translating the equivalent weight of the full system (robotic arm, end effector, and maximum cargo bag weight).
- *Verification*: **Test**
  The translation system moves the equivalent weight from one end of the track to the other.

FR 4: The end effector must be interchangeable.

- *Motivation*: SNC requires the robotics system to be able to perform an array of tasks. While the project will demonstrate only a single task, for this to be possible the end effector shall be interchangeable [3].
- *Verification*: **Test**
  Demonstrating the end effector can be removed.
- *Validation*: By enabling the system to have multiple end effectors, NASA's requirements for a system with flexible applications are satisfied.

DR 4.1: The robotic arm shall be compatible with multiple end effectors.

- *Motivation*: In order to interchange end effectors the robotic arm must be compatible with multiple end effectors.
- *Verification*: **Analysis**
  Confirmation of interchangeable end effectors shall be confirmed with the manufacturer before procuring the robotic arm.

FR 5: The translation system shall be able to navigate from one end of the track to the other.

- *Motivation*: To translate cargo through the LIFE module core, the translator must be capable of translating from one end of the track to the other.
- *Verification*: The translator starts at one end of the track and translates to the other.
- *Validation*: For the system to have operational flexibility, as specified by NASA [3], it is important the system can navigate throughout most of the LIFE module's core.

DR 5.1: The translator shall be able to move to different positions along the track with a bag.

- *Motivation*: In order to translate the cargo to the desired location(s), the translator must be capable of translating to any specified position along the track.
- *Verification*: **Test**
  The translator is commanded to specific positions along the track and it translates to that location.

DR 5.2: The translator shall be able to move to a prescribed location within a margin of 5 cm.

- *Motivation*: In order for the system to operate consistently, the translator must know its position at all times to facilitate transportation and other tasks. Since the track length will be approximately 2.5m, this will be 2% accuracy.
- *Verification*: **Test**
  The translator is commanded to specific positions and navigates to that position within +/- 5 cm.

FR 6: The end effector shall be able to control cargo while in transit.

- *Motivation*: For the system to facilitate cargo transportation, it will be necessary for the end effector to secure cargo in transit.
- *Verification*: The end effector shall not permit cargo to detach from end effector control while in transit to end location.
- *Validation*: To ensure the safety of automated cargo transfer, the end effector should exert continuous control of cargo during the entire operation.

DR 6.1: The end effector shall secure cargo for the duration of transit from the origin to the end of the track system.

- *Motivation*: The end effector cannot be allowed to lose control of the cargo while in transit. This will prevent accidents and unnecessary damage in the system.
- *Verification*: **Test**
  The end effector will maintain uninterrupted contact with cargo while on transit.

FR 7: The system shall provide a method for verifying that a given cargo transportation task has been completed or the given task has failed beyond recovery.

- *Motivation*: If a failure condition occurs during operation, the system should not be able to further compound on previous mistakes. By operating with manual or automated failure conditions, compounding failures can be prevented.
- *Verification*: Failure conditions will be intentionally met and the system will not proceed.
- *Validation*: The system's ability to identify unsuitable cargo transport operations will enable the system added flexibility and safety as per NASA and SNC requirements [3].

DR 7.1: The operating system shall be able to determine if the cargo has been placed in a specific drop off location.

- *Motivation*: The success of a single cargo transportation operation is determined if the cargo is placed outside of the core into the access-way.
- *Verification*: **Test**
  Success will be determined once the cargo is successfully transported through the access-way by the system.

DR 7.2: The operating system shall be able to determine if the cargo is irretrievable.

- *Motivation*: The system's ability to determine if cargo cannot be retrieved will enable it to determine if failure conditions have been met.
- *Verification*: **Test**
  If the cargo cannot be moved within 5 seconds of applied force or end effector interface with cargo is not possible, the machine shall report a failure.

DR 7.3: The system shall give feedback if the operation has failed and cease operations.

- *Motivation*: To ensure that the system does not contribute to a compounding problem, the machine will cease operation after reporting a failure to human controllers.
- *Verification*: **Test**
  Once a failure condition is met the system shall cease operation.

FR 8: The translation system shall be able to maintain structural integrity under the torques and forces applied to it when moving cargo.

- *Motivation*: The linear translator will be responsible for resisting deformation forces as the cargo is transported throughout the core. To ensure its continued operation any structural deformations must be kept at a minimum.
- *Verification*: Validation can be accomplished via structural simulations in a Computer Aided Design (CAD) program utilizing computed torque and force values.
- *Validation*: Since this is a proof on concept, the strength and quality are not expected to be space grade. The system is only expected to support itself.

DR 8.1: The the rail/translator system shall not deflect more 2 mm under the combined weight of the robotic arm and cargo

- *Motivation*: In order for the system to operate repeatedly any structural deformations must be kept to a minimum to ensure the system continues to operate.
- *Verification*: **Analysis**
  CAD simulations of the constructed translation and rail systems will test for maximum deformation.

FR 9: The system shall operate within the volume of the core.

- *Motivation*: The system needs to exist and operate within the LIFE module without getting caught on the surrounding environment.
- *Verification*: The Dimensions of the system must be within certain lengths.
- *Validation*: This system is meant to eventually integrate with the LIFE module.

DR 9.1: The base of the transit system shall be less than 84 cm in width

- *Motivation*: In order to fit in between cargo modules mounted on the walls of the LIFE Module, the transit systems base must not exceed this size.
- *Verification*: **Analysis**
  Measuring the base of the transit system.

4 Key Design Options Considered

4.1 End Effectors

The end effector is the mechanism by which the robotic arm will interface with the cargo bags. It will be the primary component responsible for capturing the cargo bag and securing it during translation. The end effector will release the cargo bag at the designated drop off location. Six candidates were investigated in the end effector trade study: Velcro, a vacuum, a magnetic attachment, a gripper, a latching mechanism, and a gecko gripper. Each of the design solutions are discussed in more detail below.

4.1.1 Velcro

Velcro is the simplest solution to capture and secure cargo bags. It is lightweight, cheap, strong, and easily available. However, NASA has noted many issues with Velcro [24] learned through use on the Apollo program and the ISS. Issues have included lose hooks becoming an eye irritant as well as clogging air filters. Additionally, the adhesive is not always reliable and has been recorded to fail on numerous occasions.

Additionally, Velcro is most useful for securing cargo bags, but the end effector system is also required to release bags. This means the system would require additional hardware, software, and electronics for a release mechanism, which adds potentially significant complexity to the end effector and bag interface design. Data for Velcro was taken from the Velcro's Woven Fasteners datasheet [21]. Table 1 lists the significant pros and cons of using Velcro as the end effector.

Description	Pro	Con
Lightweight	X	
Cheap	X	
Strong	X	
Environmental Hazard		X
Must be replaced when worn out		X
Additional hardware, software, and electronics required to achieve mission tasks		X

Table 1: Velcro Pros and Cons

4.1.2 Vacuum

The vacuum end effector under investigation for the trade study is the OnRobot electrical vacuum gripper, the VG10. This end effector is designed to be compatible with multiple collaborative robotic arms, and is intended to be "plug-and-play" for easy deployment. The VG10 weighs 1.62 kg with a volume of 0.016 m^3. It requires 14.4 W of power and is capable of exerting up to 98 N. For the vacuum gripper to work the cargo bags would require a non-porous side, such as hard plastic, to give the gripper a surface for the vacuum to be effective. The data for the VG10 was taken from the OnRobot VG10 datasheet [9]. Figure 3 shows the VG10. Table 2 lists the significant pros and cons of using the VG10 end effector.

Figure 3: Vacuum Gripper

Description	Pro	Con
Capable of exerting a large force	X	
Must have a non-porous surface to pick up		X
Large power requirement		X
Comparatively high weight		X

Table 2: Vacuum Gripper Pros and Cons

4.1.3 Magnetic

The magnetic end effector under investigation for the trade study is the SMC MHM-25. This end effector utilizes pneumatic pumps to control the position of a magnet. When the magnet is forced down by air it is close enough to strongly grip a magnetic material, and when the magnet is forced back up it releases the item. The SMC MHM-25 has a mass of 0.244 kg and a volume of $8.32 * 10^{-5} m^3$. For a 2 mm thick material this gripper can exert a force of 160 N, and for a 6 mm thick material it can exert a force of 200 N. The gripper itself does not require a power source, however accompanying sensors do. The sensors for this end effector are used to determine whether the magnet is extended or retracted. They require a load voltage of 24 V and a current of 2.5 - 40 mA, for a maximum power of 0.96 W. This gripper also requires a pneumatic air system to operate, so it is not ready for operation out of the box. The MHM-25 requires air pressures between 0.25 and 0.6 MPa. Each cargo bag will need a small sheet of magnetic material on one of the sides to allow the gripper to attach.

The data for the SMC MHM-25 was taken from the SMC MHM-Series magnetic gripper datasheet [7], and the auto-switch sensors datasheet [8]. The magnetic gripper can be seen in Figure 4. Table 3 lists the significant pros and cons of using the magnetic end effector.

One potential concern with this end effector is the potential environmental impact of a magnet. The concern is that the influence of this magnet will have negative consequences on surrounding systems. After further analysis, this will not a problem with this design. Magnetic force obeys the inverse square law, $F \propto \frac{1}{r^2}$. The distance between the magnet in the MHM-25 and the workpiece required to disengage the workpiece is stated to be 17 mm [7]. Therefore we can be confident that any object outside a radius of about 17 mm from the end effector will not be affected.

Figure 4: Magnetic Gripper - SMC MHM-25

Description	Pro	Con
Capable of exerting a large force	X	
Must have a magnetic surface to hold		X
Additional components necessary for operation		X
Reusable	X	
Low power requirement	X	

Table 3: Magnetic Gripper Pros and Cons

4.1.4 Gripper

The next end effector under consideration is the OnRobot RG6 Gripper. This gripper is a two finger gripper that is versatile and flexible. It is advertised as being easily deployable. The RG6 has a mass of 1.25 kg and a volume of $2.3 * 10^{-3} m^3$. It can grip with a force of 120 N and requires from 1.4 to 15 W of power. The data for the RG6 was taken from the OnRobot datasheet [10]. The OnRobot RG6 can be seen in Figure 5. Table 4 lists the significant pros and cons of using the RG6 end effector.

Figure 5: Gripper - OnRobot RG6

Description	Pro	Con
Capable of exerting a large force	X	
Large power requirement		X
Out-of-the-Box ready	X	
Reusable	X	
Versatile functionality and uses	X	

Table 4: Gripper Pros and Cons

4.1.5 Latch

The device under investigation for the latching mechanism end effector is the R4-EM-R712-131. This device utilizes an electronic rotary push-to-close latch to secure itself to a given latching mechanism, which would be on the cargo bag itself when being used for the purposes of this project. The entire mechanism has a mass of 2.0 kg and occupies a volume of $9.41 * 10^{-5} m^3$. The operating strength for the cam of the device in the "1" direction, as shown in Fig. 7, is 100 N and the maximum force that can be applied in this direction for one-time opening of the latch electronically is 1556.9 N. The device features a trigger for manual operation which requires a force of 4 N for operation under a cam force of 100 N. The power required to operate the latch electronically is 6 W. Data for the R4-EM-R712-131 was taken from the performance data sheet [1]. Figure 6 and 7 show the R4-EM-R712-131 latching mechanism.

Figure 6: R4-EM-R712-131

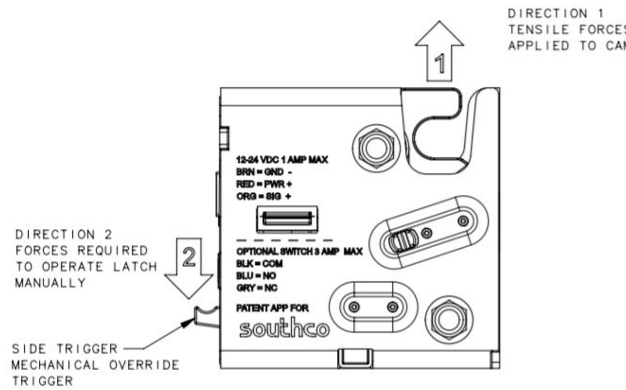


Figure 7: Performance Schematic

Table 5 shows the pros and cons of the device for end effector use within the scope of this project. Significant modification is necessary in order to use this latching mechanism as an end effector for the robotic arm. This modification would require creating an interchangeable interface to mate the device to the robotic arm. Custom software would also have to be developed to integrate it into the system. Bag modification would also be necessary in order to have attachment points at various locations on the bag to latch onto.

Description	Pro	Con
Capable of exerting a large force	X	
Requires significant modification to achieve mission tasks		X
Reusable	X	
Moderate power requirement	X	

Table 5: Latch Pros and Cons

4.1.6 Gecko Grip

The end effector under investigation for the Gecko Grip is the OnRobot Gecko SP5. This end effector uses an adhesive pad to grip surfaces. It does not require any power or compressed air to operate, making it one of the simplest end effectors being studied. The Gecko gripper weighs 0.267 kg and has a volume of $2.73 * 10^{-4} m^3$. It can exert a maximum force of 46 N. Successful operation of the Gecko Grip requires highly polished surfaces to "allow for maximum contact between the adhesive pads and the substrate surface." This means that dust or debris on the substrate surface will greatly affect the adherence to the object at hand. The specifications of the Gecko Grip assume that the center of gravity of the object is centered on the gripper pad for optimal operation. This would require precise knowledge of cargo location that would allow the end effector to be positioned optimally for grasping the cargo. Also, over time of continued use the adhesive pads will wear out and require replacement. The number of cycles before replacement is approximately 200, which during operation for the purposes of this project is not ideal. This number of cycles may be sufficient for hardware demonstration if this end effector is chosen for the baseline design. However, if the system is operating with no physical human interaction, the process of replacing the adhesive pads would increase the complexity of the system and maintenance required.

Data for the Gecko SP5 was taken from the OnRobot Gecko SP1/3/5 datasheet [11]. The Gecko Grip is shown in Figure 8. Table 6 lists the significant pros and cons of using the Gecko Grip as the end effector.

Figure 8: Gecko Gripper - OnRobot Gecko SP5

Description	Pro	Con
Capable of exerting a small force		X
Must have highly polished, solid surface		X
No electronics or compressed air necessary for operation	X	
Max of 200 cycles before maintenance		X

Table 6: Gecko Gripper Pros and Cons

4.2 Linear Transportation System

4.2.1 Ball Bearing with Conveyor Belt

Utilizing a conveyor belt with wheels for the linear transportation system would allow for a durable, high strength material belt to be used to translate the robotic arm along the track. Using ball bearings instead of pulleys (which are typical to conveyor belts) has the advantage of reducing the belt's frictional degradation, which improves the durability of the system and reduces the amount of maintenance needed (as seen in Figure 10 [23]). A potential issue with using a conveyor belt could be concerning the fastening of the robotic arm base to the belt. This can be solved by using an entirely enclosed conveyor track and attach the robotic arm to the track via mounted hooks.

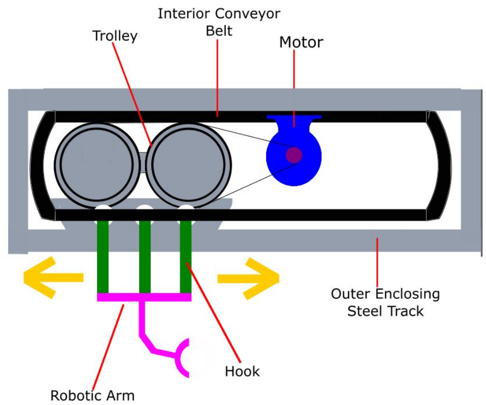


Figure 9: Conveyor Belt with Ball Bearings

The concept of the suspended conveyor design is depicted in figure 9, and the overhead track to be used is seen in Figure 11 ([22]). However, suspending the robotic arm from the ceiling of the LIFE module would prove to be complicated and delicate. A potential way to mitigate high torques on the robotic arm would be to lower the translational velocity, which affects the efficiency of transport. The relevant pros and cons of this translational system is outlined in Table 7 below (9).

Figure 10: Trolley for Overhead Conveyor

Figure 11: Overhead Track

Description	Pro	Con
Complex		X
Highly accurate	X	
Low Power Cost	X	
Fast movement		X

Table 7: Conveyor with Ball Bearing Pros and Cons

4.2.2 Wheels with Motor

The wheels with a motor design for the linear transportation system is a simple and reliable method to move the system the length of the LIFE Module's core. Using at least a dual set of wheels above and below the upper edge of the I-beam, the design could hold the translating platform to the wall of the LIFE Module without floating while one set of wheels is attached to a set of motors to propel the entire system. A potential problem with this design in zero gravity is that a wheel needs a normal force in order to roll the system forward. This normal force is created by clamping the wheels on either side of the I-beam tightly but this could cause a major increase in fiction which would drive up the power cost which the system is constrained on [6].

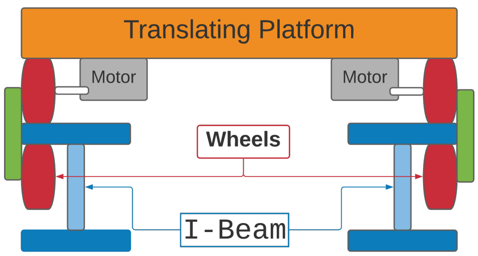


Figure 12: Front View

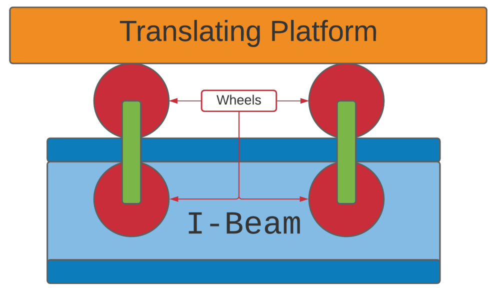


Figure 13: Side View

Description	Pro	Con
Simple	X	
Highly accurate	X	
Potentially high power cost		X
Fast movement		X

Table 8: Wheels with Motor Pros and Cons

4.2.3 Ball Bearing with Threaded Rod

The threaded rod design uses a set of parallel grooved rods with free moving ball bearing sliders that are attached to each side of a translating platform. Figure 27 is an example of this idea. The propulsion for this design will be threaded rod going through the middle of the moving platform that will rotate in order to move the platform. An example of this idea is in figure 28. This design has the benefit of being reliable in both 1G and microgravity since the translator is physically connected and will not float/slip away. The downsides to this design are its slow translation speed and need for extra materials to build the threaded rod and install it on the LIFE Module.

Figure 14: Ball-bearing Sliding Rail[4]

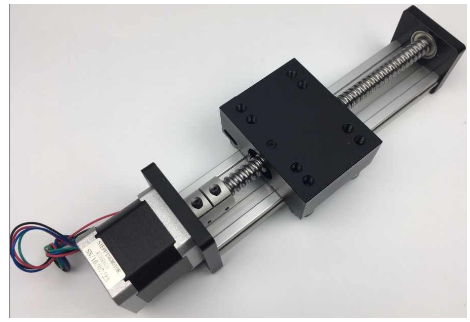


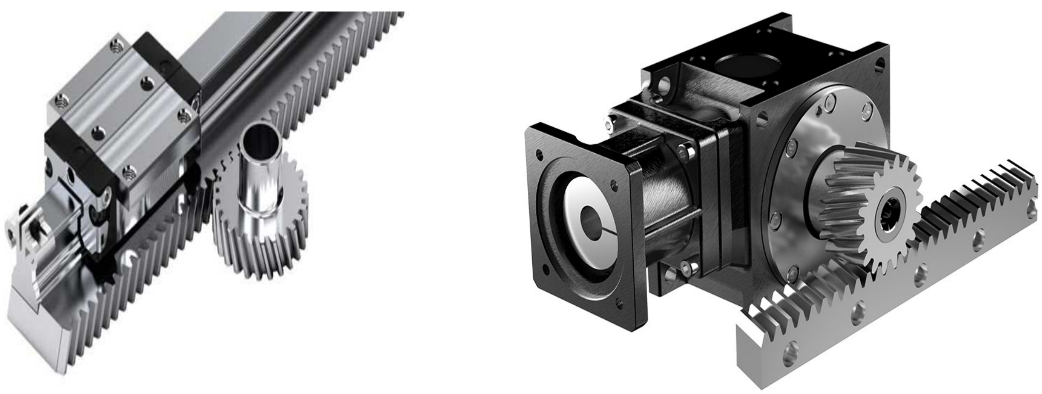
Figure 15: Threaded Rod Motor[5]

Description	Pro	Con
Simple	X	
Highly accurate	X	
Extra Materials		X
Slow movement	X	

Table 9: Ball Bearing with Threaded Rod Pros and Cons

4.2.4 Rack and Pinion

Another mechanism used in the the aerospace industry to translate robotic arms is a rack and pinion. This device drives the motion along a track. While extremely durable and capable of handling high payloads, extensive use makes this device imprecise overtime as the gears become worn. In addition, the movement of this slide needs to be programmed and calibrated to work in tandem with the robotic arm.



(a) Bosch Rexroth Rack and Pinion

(b) Rack and Pinion with motor

Description	Pro	Con
Complex		X
Weight		X
Carrying Capacity	X	
Precision	X	

Table 10: Rack and Pinion

4.2.5 Magnetic Levitation

The propulsion behind magnetic levitation is a linear induction motor. This method provides a high ceiling of force as well as velocity. Drawbacks to the linear induction motor is high weight and power consumption. A high velocity is not required for this project and isn't included in the metrics for the trade study. The linear induction motor used for this trade study is the LMAA-04-01 as shown on Figure 18. It has a maximum force of 47N, but a power consumption of 370 W. A diagram of a linear induction motor system is shown on Figure 17.

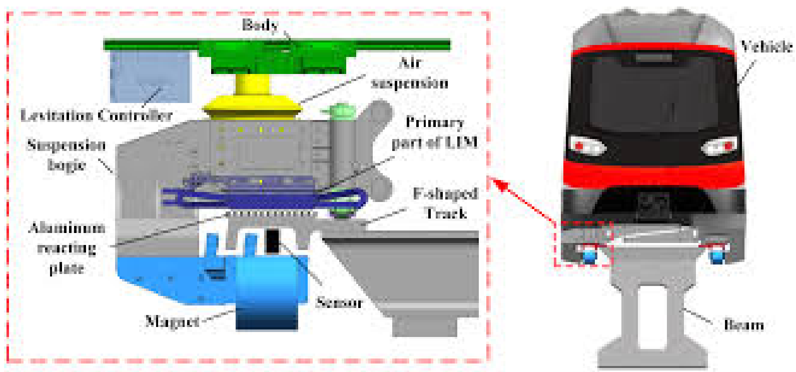


Figure 17: Example of linear induction system on a a maglev train [12].

Figure 18: LMAA-04-01 Linear induction motor[13].

Description	Pro	Con
Force	X	
Speed	X	
Power Consumption		X
Weight		X

Table 11: Magnetic Levitation Pros and Cons

4.2.6 Single Axis Linear Stepper Motor

The linear stepper motor used for this trade study is the LMSS0604-2WW0. For this trade study it is assumed the design consists of two stepper motors. The stepper motor is guided by linear roller bearings along a platen provided by the manufacturer. The platen functions as a rail in this design as shown in Figure 29. Unlike a traditional motor, a linear motor provides a direct drive instead of torque through a non-contact method. This reduces wear and tear and provides a higher degree of accuracy. The steppers each produce 26.7 N for a sum of 53.4 N. This force will be enough to satisfy DR 1.1. The power consumed by the two steppers is expected to be 19.2 W. One drawback of the stepper motor is it is an open loop control. However, using a micro-stepping drive the system is highly repeatable up to a $10\mu m$ precision. Therefore, it may be possible to run the single axis stepper motor in an automated system without needing additional sensors.

Figure 19: Single Axis Linear Stepper Motor mounted to platen [13].

Description	Pro	Con
Lightweight	X	
Low Power	X	
Precise	X	
Open Loop Control		X

Table 12: Single Axis Linear Stepper Pros and Cons /cite

4.3 Sensor Suite for Bag Configuration

In order for the IVR system to successfully unload docked cargo, a type of sensor system will need to be implemented for identifying the position and configuration of the cargo bags being unloaded. The robotics system will translate to the package that needs to be unloaded, the sensors will confirm the arm has made it to the package with minimal discrepancies. Then, the sensor system will identify the orientation of the package. This will allow the robotic arm on the transport system to effectively grip and pick up the bag for transport. Potential options to accomplish this task include lidar sensors, sonic rangers, and image processing. Data processing from these sensors will be a combination of automated software and user input.

4.3.1 Lidar Sensor

Lidar (light detection and ranging) is a method of measuring distances by pulsing a laser light at an object and leveraging measurements of the reflected light to assemble 3-D representations of the package. The return measurements include measuring the time needed for the laser to return and the associated wavelength of the reflected light. Lidar sensors have high detail and can map physical features with very high resolutions. The applications for this sensor can go as low as just range finding to as high as providing accurate terrain maps. This may allow the robotic system to distinguish the bag from the handle more easily with little effort. Disadvantages to this sensor system include environments with high light intensity. It may make it harder to measure the reflected light accurately and cause errors. There are many third party programs that produce visualizations from the outputted code from the sensor which makes it less difficult to operate the sensor immediately out of the box. [15]

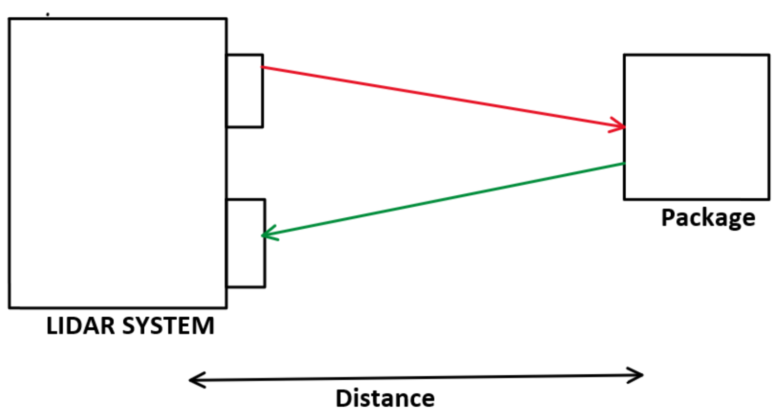


Figure 20: Lidar Diagram

Description	Pro	Con
Wide range of application (long distances, short distances, high or low detail)	X	
Highly accurate	X	
Poor operation in high intensity light		X

Table 13: Lidar Pros and Cons

4.3.2 Ultrasonic Ranger

The ultrasonic ranger operates similarly to a Lidar, but uses sound waves instead of light waves. Inherently the sound waves will travel a shorter distance than the Lidar can, however the distance of the core is still well suited for an ultrasonic ranger. This type of sensor operates by utilizing a transducer to emit a high frequency sound (higher than humans can hear) towards an object and measures the sound reflected back. The sensor can emit the sound by receiving a digital pulse from a micro-controller connected to it. Utilizing the speed of sound and the elapsed time between sending and receiving the sound wave, the distance can be determined. Similarly this same concept can be used for object detection which becomes apparent, when a signal is received or if its received sooner than expected. The only issue with object detection is the material used. Some materials can absorb the transmitted sound waves and not reflect anything back which could cause an incorrect measurement. However, unlike Lidar sensors, these can operate in a variety of uses such as high light environments, smokey areas, and even locations with no light. Ultrasonic rangers can also be powered with little power and sometimes even utilize cheap batteries. Below a diagram of an ultra sonic ranger can be seen as well as a table summarizing pros and cons. [18]

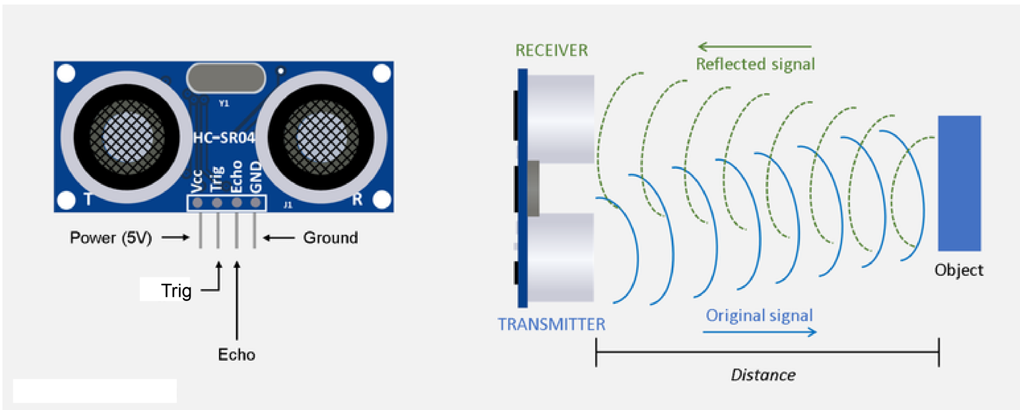


Figure 21: Sonic Ranger Diagram

Description	Pro	Con
Generally low power consumption	X	
Environmental versatility	X	
Object dependent (if bag is wool it might absorb the sound)		X
Shorter object detection range		X

Table 14: Sonic Ranger Pros and Cons

4.3.3 Image Processing

The act of image processing to detect and determine the range of objects involves using a camera or cameras to capture an image of the area. Then a computer algorithm analyzes the objects in the photo to produce useful data. The majority of this task is heavily software dependent. There are multiple third party libraries that can be utilized for either microprocessors or full sized computers respectively. Regular cameras can be utilized, however a better option is an RGB-D camera which utilizes a camera as well as a depth sensor which is an IR emitter and IR sensor that work together to measure relative depth. A computer vision technique will be used to turn the raw image data into an image that can range and identify objects with in the field of vision. High detail can be achieved with this type of sensor, especially for a relatively inexpensive price. The potential downfall for this solution pertains mostly to the high computational cost and software complexity. Two different implementations of image processing are being considered. Image processing "kit" refers to the out-of-the box complete kit with cameras equipped for motion and configuration determination. This includes the software and data processing. The other image processing option refers to constructing a kit from scratch. This would include purchasing the individual sensors, then creating the software to use the sensory information provided by the cameras to determine the configuration. [20]

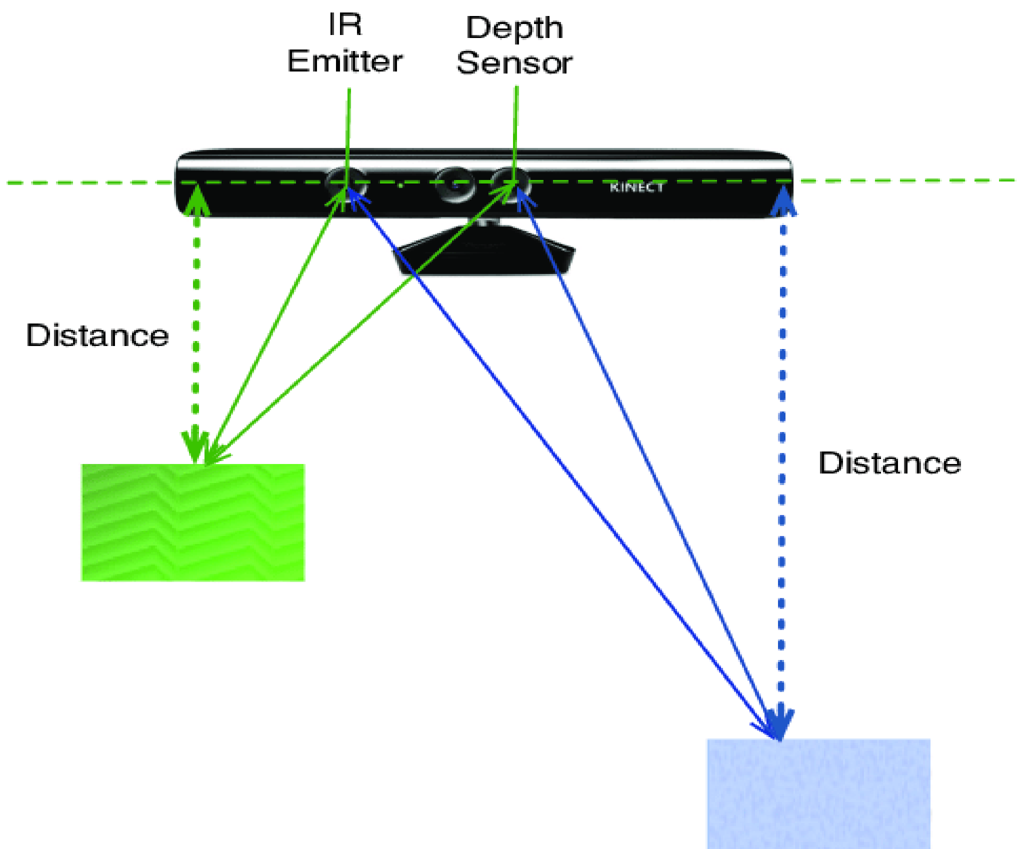


Figure 22: RGB-D Camera Diagram

Description	Pro	Con
Generally inexpensive	X	
High detailed mapping	X	
Position and orientation	X	
Computationally expensive		X
Long processing times		X

Table 15: RGB-D Pros and Cons

5 Trade Study Process and Results

5.1 End Effector

The evaluations of the end effector solutions were based on seven metrics: mass, volume, strength, out-of-the-box readiness, cargo bag modification, mating, and power requirements. The goal is to evaluate the possible design solutions using clear, objective metrics to avoid bias. During research of different end effectors each of these metrics proved to be important distinctions between the candidates. Rationale for including the metric, the weighting of the category, and the evaluation scale are provided below for each metric.

5.1.1 Mass of End Effector

Mass is a crucial metric in space environments due to constraints launch mass. The overall mass of the system is not a hard requirement for the project since we are not designing a flight-ready system. However, we decided that it was still worth considering since the system is intended to be a proof-of-concept for a space robotic system. End effector mass was assigned a low weight as optimizing other design effects are more vital to delivering a successful system while still maintaining viability for space.

The scale for this metric was decided based on the order of magnitude of masses for the end effectors under consideration. The highest mass end effector was 1.25 kg, so the most logical scale was a linear scale from < 0.1 kg to ≥ 1 kg. Table 16 shows the scoring breakdown for the end effector mass evaluation metric.
Metric Weight: 10%

Score	5	4	3	2	1
Mass [kg]	< 0.1	0.1 - 0.39	0.4 - 0.69	0.7 - 0.99	≥ 1.0

Table 16: End Effector Mass Scoring Breakdown

5.1.2 Volume of End Effector

Driving Design Requirements: DR 9.1
Similarly to the mass of the system, volume is another important metric to consider for space systems since launch volume and operating volume are both limited. Evaluating the volume of the end effector candidates ties directly into Design Requirement 9.1 for the overall volume of the system. It's important to minimize the volume of every sub-component of the system to ensure that it doesn't take up more volume than necessary. The volume of the end effector is small compared to the volume of other sub-components, so this metric received a low weighting.

The largest volume of the end effectors under investigation is 0.016 m^3. Therefore, the evaluation scale was linear from < 0.001 to ≥ 0.01 m^3. Table 17 shows the scoring breakdown for the end effector volume evaluation metric.
Metric Weight: 10%

Score	5	4	3	2	1
Volume [m^3]	< 0.001	0.001 - 0.0039	0.004 - 0.0069	0.007 - 0.0099	≥ 0.01

Table 17: End Effector Volume Scoring Breakdown

5.1.3 Strength

Driving Design Requirements: DR 1.2
The strength of the end effector determines the force that the system can apply to transport cargo bags through the LIFE module. A larger force means that the system is capable of moving bags more quickly, which is desirable. DR.1.2 dictates that the end effector must be capable of lifting a 5 kg bag in 1G, setting a minimum force that must be applicable by the end effector.

The scale for the strength metric was determined by the operating range of forces. The minimum is set to the minimum force outlined in Design Requirement 1.2. The increment between scores was set to 5 N so that the max score of 5 was approximately equal to the maximum force that the UR-10 robotic arm can apply, which is approximately 100 N. Table 18 shows the scoring breakdown for the end effector strength evaluation metric.
Metric Weight: 20%

Score	5	4	3	2	1
Strength [N]	> 96	90 - 95	85 - 90	80 - 85	< 80

Table 18: End Effector Strength Scoring Breakdown

5.1.4 Out-of-the-Box Readiness

The out-of-the-box readiness design score is intended to capture the amount of work that will be required to develop a particular end effector for the system design. This metric could save/require a significant amount of work depending on the solution, so it was given a weight of 15%, higher than mass and volume. This category refers to three essential tasks of the end effector which are defined as: (1) Grab the cargo bag, (2) Secure the bag during translation, and (3) Release the bag. The best score corresponds to an end effector that is capable of completing all three essential tasks with no modifications necessary. To keep the scores as objective as possible, the following scores were defined based on the scope of modifications that would be necessary for a given end effector, including a custom robotic arm mount and modifications to hardware, software, and/or electronic systems. Table 19 shows the scoring breakdown for the end effector out-of-the-box readiness evaluation metric. The table is intended to read: "Capable of all three essential tasks {individual score text here}".
Metric Weight: 15%

Score	5	4	3	2	1
Out-of-the-Box Readiness (Capable of all three essential tasks:)	without modification	with custom robotic arm mounting necessary	with modifications to one of the three: Hardware, Software, or Electronics	with modification to two of the three: Hardware, Software, or Electronics	with modification to all Hardware, Software, and Electronics

Table 19: End Effector Out-of-the-Box Readiness Scoring Breakdown

5.1.5 Bag Modification

Bag modification is a metric intended to capture the mass that would be added to each bag to accommodate the cargo bag interface with the end effector. Since the bag modification would have to be added to every bag, it is weighted more heavily than the mass of the end effector. The bag size was estimated using the standard half Cargo Transfer Bag (CTB), which is one of the standard bags used on the ISS. The mass added to each bag was estimated for each end effector. For some end effectors the dimensions of the bag were used to estimate the additional mass required, while others were estimated by potential attachment points.

The scale for bag modification was set to start at 0 kg for a score of 5 (indicating no bag modifications), with 1 kg increments between scores, up to > 3 kg. Table 20 shows the scoring breakdown for the end effector bag modification evaluation metric.
Metric Weight: 15%

Score	5	4	3	2	1
Bag Modification [kg]	0	0 - 1	1 - 2	2 - 3	$>$ 3

Table 20: End Effector Bag Modification Scoring Breakdown

5.1.6 Mating

The mating evaluation metric is intended to capture the ease of mating the end effector with a cargo bag. To keep our scoring breakdown objective, this metric was measured based on the number of precise degrees of freedom required of the end effector to mate with a cargo bag. 6 DOF would mean that position and orientation of the end effector is required to be precise to mate (i.e. a latch style end effector). 3 DOF means that only position is required to be precise to mate with a bag (i.e. a gripper style end effector). 0 DOF means that the end effector does not need precise positioning or orientation to mate with a bag (i.e. a magnet or vacuum end effector). This metric will add complexity to the operation of the system, so it is worth considering. However, the robotic arm will have the capability of 6 DOF motion, so it is given a low weight. Table 21 shows the scoring breakdown for the end effector mating evaluation metric.
Metric Weight: 10%

Score	5	4	3	2	1
Mating	0 DOF	—	3 DOF	—	6 DOF

Table 21: End Effector Mating Scoring Breakdown

5.1.7 Power Requirements

Driving Design Requirements: DR 2.1
The final evaluation metric for the end effector is its power requirements. Power is a very limited resource for components of a space mission, so it is an important metric to consider. While this is not a flight quality system there is still an objective to transition the system to a real solution one day.

The power draw of the end effectors under investigation is on the order of 0 - 10 W, so the scoring scale for the metric was set linearly between < 1 W and ≥ 10 W. Table 22 shows the scoring breakdown for the end effector mating evaluation metric.
Metric Weight: 20%

Score	5	4	3	2	1
Power [W]	< 1.0	1.0 - 3.9	4.0 - 6.9	7.0 - 9.9	≥ 10.0

Table 22: End Effector Power Scoring Breakdown

5.1.8 End Effector Trade Study Results

The results of the end effector trade study are shown below in Figure 24. The scores of the trade study indicate that the top three design choices for the end effector are (1) the Magnetic gripper end effector, (2) Velcro, and (3) the Gripper. The evaluation of the trade study results will be discussed further in Section 6.

End Effector							
Metric	**Weight**	**Velcro**	**Vacuum (VG10)**	**Magnetic (MHM-25)**	**Gripper (RG5)**	**Latch (R4-EM)**	**Gecko Grip (SP5)**
Mass [kg]	10.0%	5	1	4	4	5	4
Volume [m^3]	10.0%	5	1	5	4	5	5
Strength [N]	20.0%	5	5	5	5	5	1
Out-of-the-Box Readiness	15.0%	1	5	2	5	1	4
Bag Modification [kg]	15.0%	5	4	4	4	3	3
Mating	10.0%	3	5	5	3	1	3
Power [W]	20.0%	5	1	5	1	3	5
Total	100.0%	4.2	3.25	4.3	3.65	3.3	3.45

Figure 23: End Effector Trade Study Results

5.2 Linear Transport System

The linear transport system trade study was constructed by combining the propulsion and means of translation for the system. These components couldn't be evaluated separately due to their co-dependency. Metrics for this system were determined using design requirements: DR 1.1, DR 2.2, DR 2.3, DR 3.1, DR 3.2, DR 5.1, DR 5.2, DR 8.1 and DR 9.1. The metrics selected for this trade study are: mass of translator, supporting force, translation force, repeat-ability, precision, localization and power requirement.

5.2.1 Mass of Translator

Driving Design Requirements: DR 1.1, DR 3.1
The translator mass metric is specific to section of the translation system that will be moving with the robotic arm. This does not include the rails, or other stationary aspects of the system. The motivation for this metric is the need for the system to be tested in 1G and the desire for the translation to accelerate at .03 m/s^2. The lower the mass of the translator, the easier it will be to accelerate.
Metric Weight: 10%

Score	5	4	3	2	1
Translator Mass[kg]	0-2	2-4	4-6	6-8	>8

5.2.2 Supporting Force

Driving Design Requirements: DR 3.1
Supporting force is a metric to ensure that the translation system can support the torques and Forces created by the robotic arm. This metric is driven by the requirement for the system to be validated in a 1G environment. The force was calculated using a mass of 33.5kg for the arm and 10 kg for the maximum payload. This totals to 435 N using newtons second law. The corresponding moment is 348 Nm with the moment arm being at an average length of 0.8 meters.
Metric Weight: 10%

Score	5	4	3	2	1
Supporting Force(N)	>500	499-484	483-468	467-451	450-435
Supporting Moment(Nm)	>348	347-300	299-251	250-202	201-155

5.2.3 Translation Force

Driving Design Requirements: DR 3.1
Translation force determines the system's acceleration while translating along the length of the LIFE module's core. A higher force enables greater acceleration with equal amounts of cargo. Due to the emphasis on safety and reliability over speed, this particular metric was given a weight of 10% to reflect its importance in demonstrations for a 1G environment and this metric's usefulness in zero-g.
Metric Weight: 10%

Score	5	4	3	2	1
Translation Force [N]	>30 N	25-30N	20-25 N	15-20 N	<15N

5.2.4 Repeat-Ability

The repeat-ability metric is included to ensure that the system can run off the resources provided in the LIFE module with little to no maintenance as well as taking into consideration the overall wear and tear on the components due to use. For example, propulsion methods such as compressed air would require additional resources other than the electricity provided to the module. The air could be compressed on board, however this would drastically increase the complexity of the system. Also, certain design options have many moving parts that constantly experience friction causing damage over a long period of time. As such the repeat-ability metric is included to reduce complexity in the system and ensure the design has high longevity with the given resources.
Metric Weight: 15%

Score	5	3
Repeat-ability Translation operation dependency on outside resources	Translation operation is entirely repeatable with provided resources	Translation operation requires intervention or resupply for continued operation

5.2.5 Precision

Driving Design Requirements: DR 5.2
The precision metric ensures that the translation system is able to exceed DR 5.2. Although the design requirement only requires a precision of 5 cm the translation systems researched were easily able to hit this value. However, especially for systems with open loop localization it is essential that the system is able to move precisely enough for the process to be automated for multiple cycles. To account for this the scoring for precision was constructed between 0-7mm.
Metric Weight: 20%

Score	5	4	3	2	1
Precision [mm]	<1	1-3	3-5	5-7	>7

5.2.6 Localization

Driving Design Requirements: DR 5.1 The localization metric is based on how complicated the methods are for the system to determine it's position along the track. If the system is able to determine it's position out of the box it is given a 5, while if the system will need an additional sensor suite, it is given a 1. This metric is included in the trade study in an attempt to minimize the hardware and software complexity of the required position tracking system.
Metric Weight: 15%

Scoring	5	3	1
Localization	System includes closed loop localization	Precise open loop control localization resources to repeat	External sensor suite required for localization

5.2.7 Power Requirement

Driving Design Requirements: DR 2.2, DR 2.3
The power requirement metric is important to include as any space-borne mission will involve power limitations. Due to the influence of power restrictions from the flight-ready hardware specified by SNC, it was decided active power not exceed 300 W based on hardware options available. With this being a hard requirement the scoring for this metric is set between 0-300 W. The lower end of scoring is set at 0 W because less power consumption will allow more margin for power surges and more power allotment for other sections of the IVR system.
Metric Weight: 20%

Score	5	4	3	2	1
Input Power[W]	0-60	60-120	180-240	240-300	>300

5.2.8 Linear Transport System Trade Study Results

Below are the results of all the Translation system options being evaluated based on the criteria previously examined in the prior sub sections of 5.2. Certain qualities are weighted more heavily than others based on Functional requirements given to us by Sierra Nevada Corporation. The design options are evaluated on a zero to five scale being a sum of the scores in each category times the weight of each category.

Linear Transportation System							
Metric	Weight	Maglev	Conveyor	Rack and Pinion	Threaded Rod	Motorized Wheels	Single Axis Stepper
Mass of Translator [kg]	10.00%	4	2	3	4	3	5
Supporting Force [N, Nm]	10.0%	5	5	4	5	3	5
Translation Force [N]	10.0%	5	3	4	5	3	5
Reusibility	15.0%	5	3	3	3	3	5
Precision [mm]	15.0%	4	4	4	5	5	5
Localization	20.0%	3	3	3	5	5	3
Power Requirements [W]	20.0%	1	4	3	2	3	5
Total	100.0%	3.55	3.45	3.35	4	3.7	4.6

Figure 24: Translator Trade Study Results

5.3 Sensor Suite for Bag Configuration

The Sensor Suite trade study was evaluated based on DR 2.1, DR 6.1, DR 7.1, DR 7.2, and DR 7.3. The metrics selected for this trade study are: software complexity, accuracy, range, mounting capability and field of view, ability to determine bag versus environment, and power requirements. This section will explain the rationale for including each metric in the analysis, along with the weight of each category and the evaluation scale.

5.3.1 Software Complexity

Driving Design Requirements: DR 7.1, DR 7.2, DR 7.3
Software complexity was included to evaluate the scope and efficacy of the software needed to take the sensory information and convert it into a position and orientation measurement. While

complexity is a factor in time investment, it was determined that the quality of the sensor suite should be weighted more heavily as good data decreases the need for software complexity to process data.
Metric Weight: 10%

Score	5	4	3	2	1
Software Complexity	Out of the box functionality and localization	NA	NA	NA	Coding functionality from scratch using only sensory information

Table 23: Software Scoring

5.3.2 Accuracy

Driving Design Requirements: DR 6.1, DR 7.1
Accuracy refers to the accuracy of the sensed position and orientation relative to the true position and orientation. 3cm was chosen as the lower translational accuracy bound to allow the object to attach to the end effector. 3cm can be the difference between the end effector being able to grasp the cargo versus missing the cargo. The lower bound refers to a system that can meet the minimum translational requirement, but cannot measure orientation of the object. An ideal sensing system would be able to measure position and orientation with a high level of accuracy at range. Having a high level of accuracy not only allows for a more reliable "pick-up" of objects, but also can decrease the discrepancy between the knowledge of the operating system and the actual status of the environment. This can affect robot motion planning and collision. Due to the high impact of improvement in this metric, accuracy was weighted heavily.
Metric Weight: 20%

Score	5	4	3	2	1
Accuracy	Location of objects determined to within .3cm and 3 degrees	2.1 cm $17°$	1.2 cm $31°$	3.0 cm $45°$	3cm no orientation

Table 24: Sensor Accuracy Scoring

5.3.3 Range

Driving Design Requirements: DR 6.1, DR 7.1,
The range metric was included to account for the sensor suite's ability to span the entire core. This metric, in tandem with the "Mounting Capability and FOV" metric allow for classifying the ability for a solution to be able to determine location of cargo. The sensor range upper bound (besides "infinite" range) is slightly larger than the length of entire core. The lower bound was determined assuming that both the bag and the end effector are present at the pickup hatch. The minimum sensing distance in this scenario is the radius of the pickup hatch, assuming the end effector is at the center of the hatch (determined from the CAD model), and the bag mate will be closer to the end effector than the edge of the hatch. This lower bound scenario assumes that the sensor suite is attached to the end effector, while the upper bound does not include this assumption. The weighting of range was chosen to lie in between software complexity, but also not take the highest weight. This is motivated by the requirement of being able to determine success or failure. Being

able to observe the entire work space is imperative to this requirement, however, if a system does end up scoring low on the range metric, more sensor groups can be included to extend the range. This was the motivation for weighting this metric moderately.
Metric Weight: 15%

Score	5	4	3	2	1
Range	∞	5.6m	3.9m	2.3m	0.63m

Table 25: Sensor Range Scoring

5.3.4 Mounting Capability and FOV

Driving Design Requirements: DR 6.1, DR 7.1, DR 7.2
Mounting Capability and Field of View refers to the ability for the entire sensor suite to capture the spaces that need to be analyzed. Mounting capability refers to the possible positions that a single (or subgroup of) sensor(s) can be mounted such that the field of view is not obstructed. The upper bound captures sensing systems that are not obstructed the walls of the core or the obstacles within the core. The lower bound refers to sensing systems that have a very restricted FOV, and thus many sensors (or many subgroups of sensors) are needed to be able to extensively determine state of the work space. Mounting Capability and FOV is complimentary to the "Range" metric. The consequences for a low score on this metric are similar to that of "Range" in that increasing the amount of sensor groups can solve the short-comings. This will add both system complexity and software complexity. The increase in complexity along with the existence of a possible "work-around" motivates the moderate weighting.
Metric Weight: 15%

Score	5	4	3	2	1
Mounting Capability and FOV	Full spherical FOV, not dependent upon mounting location	Can be mounted in most places within the core while maintaining full necessary FOV (1 sensor)	2 sensor groups are needed	4 sensor groups are needed	Mounting location heavily restricted by the FOV, more sensors are needed for full localization.

Table 26: Sensor FOV and Mounting Scoring

5.3.5 Ability to Distinguish Bag

Driving Design Requirements: DR 6.1, DR 7.1, DR 7.2
The ability to distinguish what is a bag and what is only part of the environment is incredibly important when considering sensor suites. The sensory data that is being output from these sensor suites must be able to be used to determine where a bag or piece of cargo is. This is how completion or irreversible failure is defined with respect a given task. The upper bound ideal case refers to a sensor suite that outputs information that only refers to configuration properties of the cargo while ignoring other collision obstacles and work space bounds. The lower bound refers to a system

that requires additional hardware and/or software to be able to distinguish the bag from other environmental obstacles. This metric was heavily weighted to emphasize the importance of object differentiation between the environment and system objectives in this project. If a solution scores low on this metric, the sensory information provided by this sensor system is much less value able to the operating system, and would likely need to rely on included hardware to be able to determine where the bag is.
Metric Weight: 20%

Score	5	4	3	2	1
Determining Bag vs Environment	Sensor only recognizes bag	NA	NA	NA	Additional hardware or software needed to differentiate bag from the environment

Table 27: Determining Bag vs Environment

5.3.6 Power Requirements

Driving Design Requirements: DR 2.1
The sensors will utilize the smallest portion of the available power budget, but it's still crucial to budget and monitor to prevent any electrical failures. If the sensor can't meet power requirements, then the entire system may fail without proper bag orientation detection. This is the reasoning behind giving this sensor requirement the highest weighting. A maximum allocation of 50 watts or higher was allocated for the worst case power requirement of a sensor. The best case scenario was 10 watts or less and power requirements were linearly mapped for the intermediate scores. A summary of the scoring breakdown for sensor power can be seen below. The weighting of this metric is one of the three major factors to consider for this subsystem due to the hard-line limitations associated with power consumption.
Metric Weight: 20%

Score	5	4	3	2	1
Power [W]	0 - 10	10 - 20	20 - 30	30 - 40	>50

Table 28: Sensor Power Scoring

5.3.7 Sensor Suite Trade Study Results

Below are the results of all the sensor suite options being evaluated based on the scoring criteria. As can be seen by the results, the two best options are either image processing or an image processing kit with user friendly interfacing and software.

Sensor for Bag Configuration					
Metric	Weight	Lidar Sensor	Sonic Ranger	Image Processing Kit	Image Processing
Software complexity	10.0%	1	1	5	1
Accuracy	20.0%	1	1	5	5
Range	15.0%	5	4	4	4
Mounting capability and FOV	15.0%	3	3	3	3
Ability to Distinguish Bag	20%	1	1	5	5
Power Requirements	20.0%	5	5	1	1
Total	100.0%	2.7	2.55	3.75	3.35

Figure 25: Sensor Suite Trade Study Results.

6 Selection of Baseline Design

6.1 End Effector

The SMC MHM-25 Magnetic gripper scores particularly well in each of the evaluated metrics, particularly power usage and strength, which are the two highest weighted. The most significant drawback of the SMC MHM-25 is that it requires additional hardware to function. The MHM-25 uses compressed air to extend and retract the magnet, so it requires a separate air compressor, as well as pneumatic tubing and software to control its actuation. These additional materials, however, can all be acquired commercially and assembled, making it a minor drawback of this design.

Velcro scores very well in all categories except out-of-the-box readiness, which it scores very poorly. Specifically, Velcro would require a custom mount for the robotic arm, as well as supplemental hardware, software, and electronics to release a cargo bag. Additionally, Velcro introduces environmental hazards and issues that none of the other end effectors do. These issues would require significant effort to solve, which is not reflected in the high score Velcro receives.

The RG6 robotic arm gripper received the third highest score from the end effector trade study. It scored well in most categories except for power consumption, in which it received a 1. The RG6's most significant positive attribute is its out-of-the-box readiness. This end effector is the only one (of the top three designs) that is capable of grabbing a cargo bag, securing the bag during translation, and releasing the bag without any modifications.

After evaluating both the results of the end effector trade study and the pros and cons of the top three designs we have decided that our baseline design will include the SMC MHM-25 Magnetic Gripper. The MHM-25 scores slightly higher than Velcro, but the drawbacks of Velcro are significant enough to remove it from consideration. Additionally, the MHM-25 scores sufficiently higher than the RG6 to justify selecting the MHM-25 for our baseline design. This design option provides the best solution to our design problems, with the most minor drawbacks.

Figure 26: MHM-25

6.2 Translator

The two highest graded solutions from the trade study are the threaded rod and single axis stepper motor. Both of these solutions use ball bearings to reduce friction and help support the payload. The category the threaded rod scored lowest in is the power requirement, while the single axis stepper scored lowest in localization. Both of these solutions are able to fulfill the design requirements.

Figure 27: Ball-bearing Sliding Rail[4]

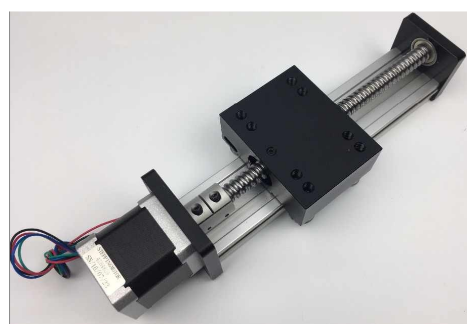


Figure 28: Threaded Rod Motor[5]

Figure 29: Single Axis Linear Stepper Motor mounted to platen [13].

The threaded rod solution would consist of a custom rod in between the two rails. The torque and velocity of the translator could be altered by changing the thread count on the rod. The system is relatively simple and should be able to effectively meet the design requirements. However, one concern with the threaded rod system is either a rod would need to be extended in between the two rails, or there would need to be a rod on both sides of the translator. This symmetry is important to prevent torque on the supporting structure. The problem with one rod in the middle, is it prevents cargo from being placed in-between the rails. If two rods are to be used this would increase power requirements and complexity in the system. Also a rod that endures a frequency of payloads is prone to distortion over time.

The single axis stepper provides linear translation with high precision. For reuse-ability, the single axis stepper doesn't require contact with the surface of the platen which will reduce wear and tear over time. The largest concern with this design is that it requires a custom platen that would be provided by the manufacturer. The system accounted for in the trade study accounts for a stepper motor on each rail, which would require two platens. Currently the team is waiting on a quote from H2W technologies to determine if this solution will be within the teams budget.

Both of these methods are able to properly hit the design requirements. For now the team is selecting the single axis stepper(LMSS0604-2WW) as the baseline design. However, this may be subject to change depending on whether the quote is within budget. The threaded rod method should also be able to succeed in reaching design requirements if needed to fallback on this method. To increase confidence in the selection of this trade study the team will run preliminary models on the threaded rod and single axis stepper until a stronger conviction is reached.

6.3 Sensor Suite for Bag Configuration

The results of the trade study found the two best options to be an image processing kit with user friendly interfacing and software followed by a stand-alone image processor. The only real difference between these two is the software. Given their close similarity and their relatively close scores these two options will be discussed more in terms of a down selection for a baseline design. Self designing an image processing system and software will serve as a backup option, if the budget does not allow for the use of a dedicated image processing kit.

The Lidar Sensory as well as the Sonic Ranger scored low on the trade study mainly due to the Accuracy (most notably the lack of orientation accuracy) as well as the Ability to Distinguish the bag from the environment. The scoring for these two options ended up being similar, which is reflective of the similar physical nature of analyzing disturbance between a projected and received signal. Lidar could potentially distinguish orientation, but it takes a highly trained human eye to reliably notice slight differences. Therefore it would be even more difficult to teach a machine to learn the differences. This why Lidar scored very poorly in accuracy. Both lidar and the sonic ranger would need another sensory suite in conjunction to operate within the desired requirements.

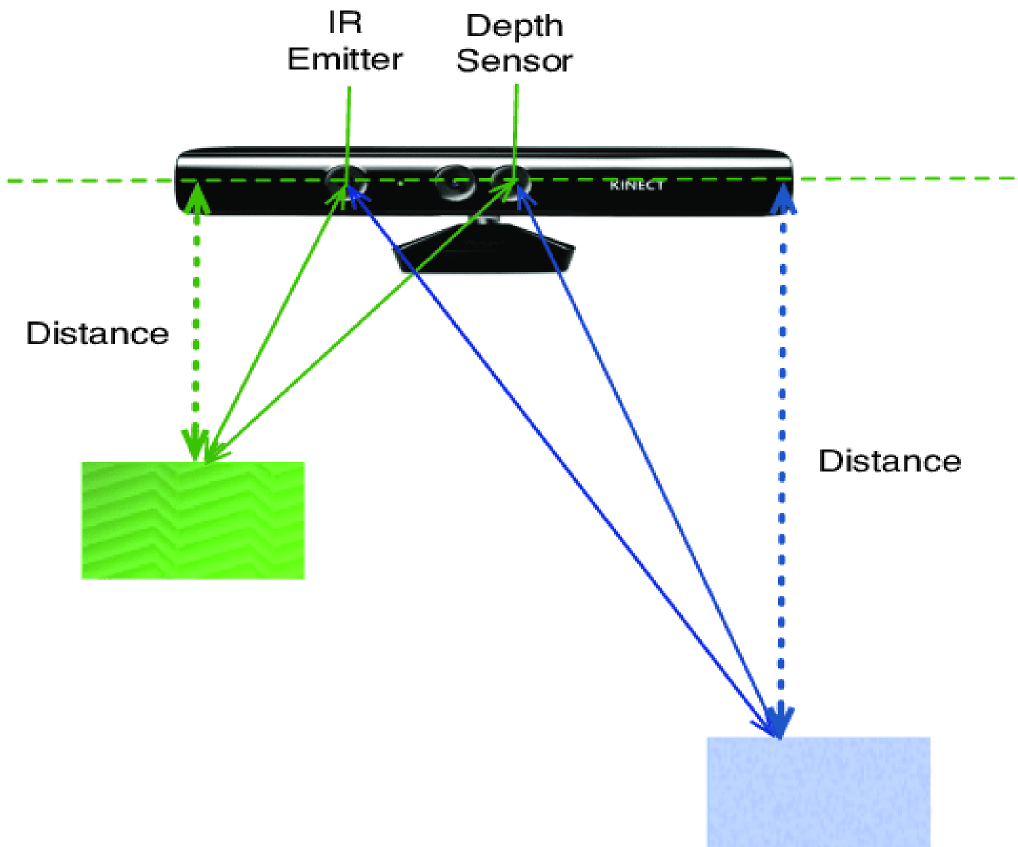


Figure 30: RGB-D Camera Diagram

Bibliography

[1] "R4-EM-R712-131." *Southco*, `southco.com/en_us_int/r4-em-r712-131`.

[2] Akin, D. L. (2015). CTB Information [PDF]. College Park: University of Maryland.

[3] McDaniel, L. (2020, September 10). SNC IVR Requirement Matrix for CU_v2 [XLSX]. Boulder: Sierra Nevada Corporation.

[4] "Threaded Rod Linear Guide Rail with Motor Ballscrew for Cnc Ball Screw Linear Module for 3d Printer Parts Robotic: |." AliExpress, www.aliexpress.com/i/32885112239.html.

[5] "Height Roller Rail System." MSC Industrial Supply - Metalworking Tools and MRO Supplies, MSC, www.mscdirect.com/product/details/00372870.

[6] "BLHM5100KCM-30 / BLHD100K, 100 W (1/8 HP) Brushless DC Motor Speed Control System (30:1 Gear Ratio) (24 VDC)." Oriental Motor USA, catalog.orientalmotor.com/item/blh-series-brushless-dc-motor-speed-control/100w-blh-brushless-dc-motor-speed-control/blhm5100kcm-30-blhd100k.

[7] "MHM-Series Magnetic Gripper." *SMC*, `https://content2.smcetech.com/pdf/MHM.pdf`

[8] "Auto Switch Guide. Page 1288", *SMC*, `https://www.smcpneumatics.com/pdfs/AutoSw-Guide.pdf`

[9] "VG10." *OnRobot*, `https://onrobot.com/sites/default/files/documents/Datasheet_VG10_v2.0_ENGLISH.pdf`

[10] "RG6." *OnRobot*, `https://onrobot.com/sites/default/files/documents/Datasheet_RG6_v1.2_EN_0.pdf`

[11] "Gecko SP1/3/5." *OnRobot*, `https://onrobot.com/sites/default/files/documents/Datasheet_GeckoSP_v1.0_EN.pdf`

[12] Yang, Y, et al. "Study on the Optimization of Linear Induction Motor Traction System for Fast-Speed Maglev Train." Edited by J Deng, CRRC Zhuzhou Locomotive CO., pp. 156–164.

[13] "AC Linear Induction Motor - LMAA-04-01." H2W Technologies, www.h2wtech.com/product/linear-induction/LMAA-04-01.

[14] "Single Axis Linear Stepper Motors." H2W Technologies, www.h2wtech.com/category/single-axis-linear-stepper.

[15] Wasser, L. A. (2019). "The Basics of LiDAR - Light Detection and Ranging" *NSF NEON*, `https://www.neonscience.org/lidar-basics`

[16] "LiDAR Specification Comparison Chart" *Autonomous Stuff*, `https://autonomoustuff.com/lidar-chart/`.

[17] Collins, Danielle. (2016). "Linear Motion Tip" A design world resource, `www.linearmotiontips.com/profiled-rail-rack-pinion-integrated-solution`

[18] Burnett, R., "Understanding How Ultrasonic Sensors Work," *MaxBotix Inc.* https://www.maxbotix.com/articles/how-ultrasonic-sensors-work.htm

[19] "XL-MaxSonar® - EZ™ Series Data Sheet", *MaxBotix Inc.* https://www.maxbotix.com/documents/XL-MaxSonar-EZ_Datasheet.pdf

[20] Lu, Yao. "RGB-D Sensors and Applications [pptx]", *University of Washington*

[21] "Woven Fasteners.", *Velcro*, https://s23775.pcdn.co/wp-content/uploads/sites/2/2017/02/VELCRO-Brand-Woven-Fasteners.pdf

[22] "10 Feet Long Straight Track for Overhead Enclosed-Track Conveyor," *McMaster* https://www.mcmaster.com/5927K11

[23] "Trolley for Manual Overhead Enclosed-Track Conveyor," *McMaster* http://www.mcmaster.com/5927K42

[24] "Fastenings: Velcro", *Working on the Moon: Lessons from Apollo*, https://history.nasa.gov/alsj/WOTM/WOTM-Velcro.html

7 Appendix

7.1 Team Organization

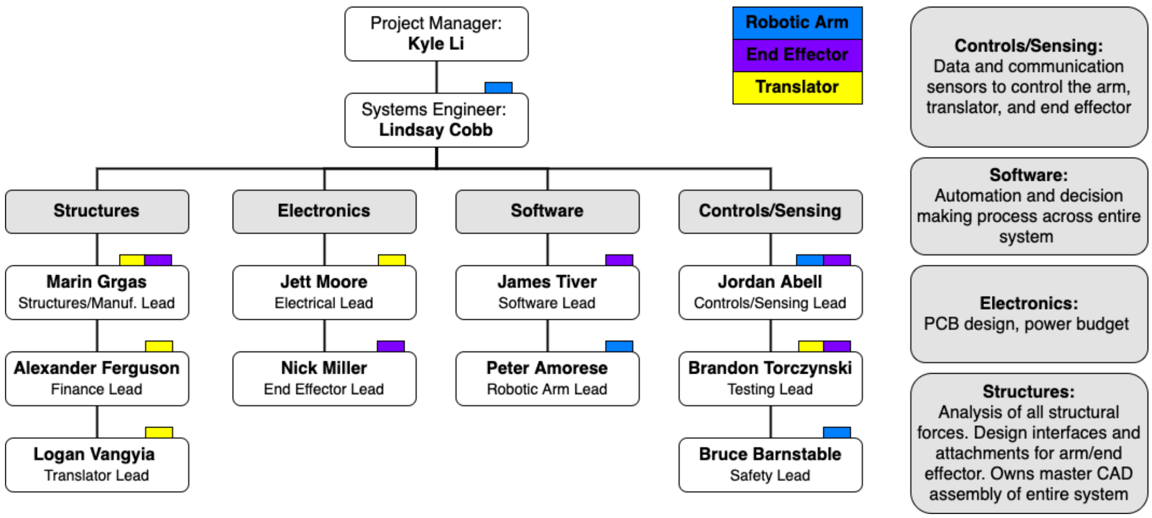


Figure 31: Org Chart