

**Customized Science Carrier Modules and Accessories
Developed for Microgravity Simulation Devices**

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6. Accessories. Torres J, Richards J, Gleeson J, Neelam S, Udave C, Zhang Y.

Technical Publication

Customized Science Carrier Modules and Accessories Developed for Microgravity Simulation Devices

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1.0 Abstract

Because the access to the true weightless environment of the ISS and other Low Earth Orbit (LEO) vehicles is limited and cost prohibitive, the need for ground-based microgravity simulation analogs to bridge the gravity continuum gap between 1g gravity and costly space flight studies with true weightlessness was realized. As such, the Microgravity Simulation Support Facility (MSSF) was established at NASA John F. Kennedy Space Center (KSC) to fulfill the need of the scientific community. Our facility provides the US science community with a focal point in the field of gravitational research by granting access to an array of two-dimensional (2D) and three-dimensional (3D) clinostats, and Random Positioning Machine (RPM) platforms developed by teams throughout the world. The availability of these capabilities will allow further understanding the role of altered gravity vectors from “functional weightlessness”, partial gravity conditions (1×10^{-3} to 0.9g, and Moon and Mars ‘g vectors), to hypergravity (up to 3 g) on biological processes. We have designed and 3D printed a variety of specialized attachments (and associated “static control” hardware) to allow researchers to mount their samples onto these microgravity simulation devices to meet their unique science requirements. A summary of each attachment module will be presented below.

2.0 Introduction

The International Space Station (ISS) has provided an invaluable platform to study cellular and molecular mechanisms involved in the adaptation of humans, plants, microbes, and invertebrate and vertebrate animals to Low Earth Orbit (LEO) spaceflight environment with the absence of gravity. Data derived from many of these space biology studies have developed a much greater understanding of the complexity of how the stress of weightlessness influences these organisms from cellular damage repair, immune suppression, and bone and muscle loss in animals, to the role of auxin and statoliths in gravi-sensing in plants. As we advance closer towards much longer duration spaceflights associated with human colonization of the Moon and Mars, a deeper understanding of adaptations to microgravity is therefore required, especially with exposure during the transit phase and partial gravity environments of a Mars mission.

While the access to the true weightless environment of the ISS and other Low Earth Orbit (LEO) vehicles is limited and cost prohibitive, the ground-based microgravity simulation analogs provide affordable and readily available test platforms to investigate the role of altered gravity vectors from functional weightlessness, partial gravity conditions (1×10^{-3} to 0.9g, and Moon and Mars ‘g vectors), to hypergravity (up to 3 g) on biological processes.

A. Microgravity Simulation Devices

Supported by NASA Science Mission Directorate (SMD) – Biological and Physical Sciences Division (BPS), our Microgravity Simulation Support Facility (MSSF) was established at NASA John F. Kennedy Space Center (KSC) in 2017 to provide the US science community an array of

two-dimensional (2D) and three-dimensional (3D) clinostats, and Random Positioning Machine (RPM) platforms (Zhang *et al*, 2021). The 2D clinostat has been the basis of gravitational plant research since the early 19th century (Knight, 1806). With the development of 3D clinostats and Random Positioning Machines (RPM), we have been able to approach a potentially more robust simulation of functional weightlessness. Several studies have shown that some cellular or organismal responses to “functional weightless” generated by a 3D simulation device are similar to those to true weightlessness aboard the ISS (Kraft *et al*, 2000). 3D clinostats and the RPM units achieve simulated microgravity by rotating a sample around two independently operated axes, rather than one perpendicular axes (2D clinostat) thereby potentially reducing the influence of directional g vector and/or shear forces, especially for the samples close to the center of rotation along both axes.

B. Limitations for Supporting a Wide Variety of Science

One of the common limitations for these microgravity simulation devices is the lack of science or sample container specific carriers. This limitation leads to inconsistent results and/or unfavorable simulation conditions, e.g. increased vibration and sample to sample variation, which affect data interpretation significantly. Concomitantly, the need exists for unique experimental hardware for each visiting investigator team to retain specialized samples within the constraints of the microgravity simulators to support a wide variety of science, from plant, microbial, and cell culture, to invertebrate experiments.

3D clinostats and RPM: While there are several sample holders provided for the Gravite 3D clinostat (Space Bio-Laboratories, Japan, Figure 1A), none are provided for the RPM 2.0 unit (Airbus, Germany, Figure 1B) except for the basic baseplate for sample integration. Furthermore, experiment unique fixtures along the rotational axes are needed for placing the science at the center of the rotation axes to support unique sample containers with different sizes and shapes. In most instances, the requirements for each of these fixtures are science specific to enhance the simulation devices for a broader scope of science.

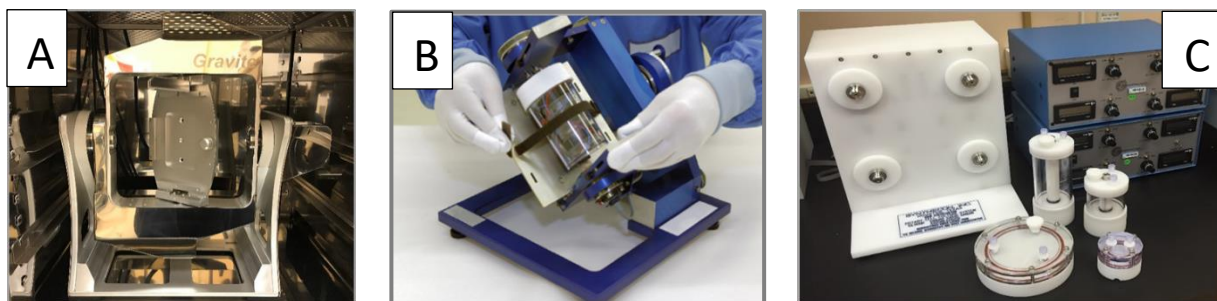


Figure 1. 3D clinostat and RPM units in MSSF. A) A Gravite 3D clinostat. B) An RPM unit. C) A Rotary Cell Culture (RCC) system.

Rotary Cell Culture (RCC) systems and 2D clinostats: In addition to simulating free fall typically used for liquid cell cultures, the RCC system (Synthecon, Houston, TX, Figure 1C) can readily be utilized as a 2D clinostat. However, there are no standard sample holders for the RCC system to

be adapted as a 2D clinostat. Furthermore, most 2D clinostats have no science specific customized sample carriers developed.

In this package, we summarize several examples of the unique sample carrier modules that we have developed in the MSSF, which are presented in the following sections.

3.0 Customized Science Carrier Modules

A. Light-Emitting Diode (LED) Light Illuminated Stage for 100mm² Petri Plates (NTR: KSC-14263, Appendix A)

A key consideration for designing hardware to accommodate plant research on microgravity simulation devices is how to provide a consistent and unidirectional light on a rotating specimen. Clearly, static fluorescent or LED lighting systems typically available in environmental growth chambers provide the appropriate wavelengths of light for plant growth, however, with the subject rotating, there are periods within the rotational cycle that the subject could be facing away from the light (e.g. plants could be upside down on a petri plate facing downwards). With phototropism and gravitropism being two interactive mechanisms in plants, inconsistency in lighting could directly affect plant growth and development, and as such, lead to misinterpretation of results.

To correct for this, a dual-lighting LED module was created to mount within the inner rotational ring of the RPM 2.0 as it has a 15-pin connector mounted on the inner rotational axes which feeds power from external power supplies (2 amps max) while the system is rotating (Figure 2A). Therefore, with the low power requirements of the LEDs, their small compact size, little to no heat production, and a great variety of off the shelf full spectrum white LED perfectly suited for plant growth, we selected the Agrivolution white LEDs as our light sources. These LEDs can provide modulated intensities greater than 300 $\mu\text{mol m}^{-2} \text{s}^{-1}$ photosynthetic photon flux density (PPFD) of broad-spectrum lighting. In addition to the Agrivolution white LEDs, other LED light strips from UV to far-red light spectrums can be used based on a requirement specifically based on each study.

This module was originally developed for a plant circadian rhythm study and resulted in the development of three custom components to meet the unique requirements for the investigation (Zhang *et al*, 2021). The RPM module allowed for dual light cycles (photoperiods) to be delivered separately to two sets of 100 mm² petri plates with *Arabidopsis thaliana* seeds/seedlings, as each set of two plates is separated from the other light treatment by an opaque black light barrier. Separate systems were also designed by coupling two test tube racks together with the identical LED lighting for supporting 1-g static controls simultaneously under the same intensity of light as those held in place on the RPM (Figure 2B). Cassette boxes were designed to hold two plates per each treatment condition and to reduce or prevent the root zone from exposure to unwanted scattered or reflected light, and to aid in the addition and removal of the petri plates from the RPM or the modified test tube racks. Hooks were 3D printed on the baseplate and rubber bands were used to secure the cassette boxes with the

two petri plates to the baseplate. The light barrier was printed on an adjacent supporting plate, all which slide together into the RPM 's inner frame.

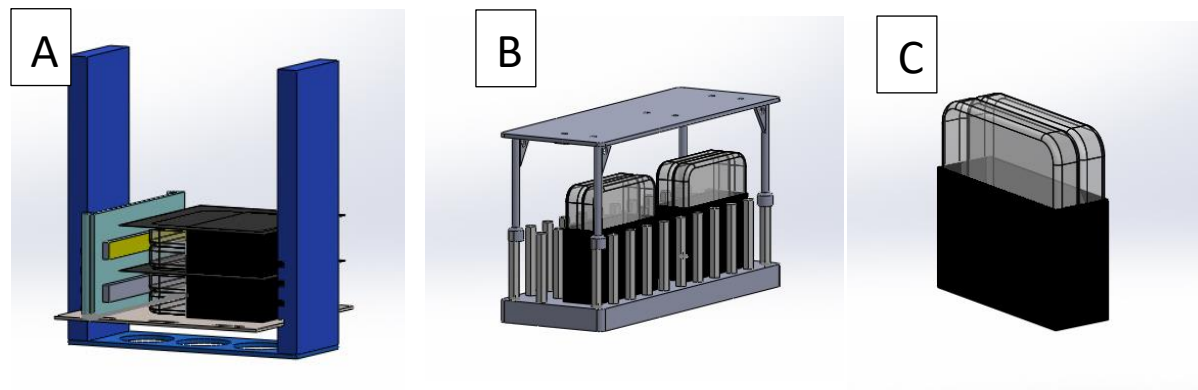


Figure 2: A) The inner rotating structure of the RPM showing two LED light strips illuminating the center of two 100mm² petri plates. The two LED strips can be set to different photoperiods as the design incorporates the addition of a black opaque barrier between the upper and lower LED light strips. B) Modified test tube holder representation of the unit “1 g” ground control plates which are illuminated by the identical LED strips at the same distance from the top of the plates, and intensity as the RPM lighting setup. C) Cassette boxes which allow for the easy addition and removal of the two 100mm² petri plates into the RPM module or the test tube rack holders. These boxes were also designed to aid in decreasing illumination of the root zone throughout the experiment, but still allow for proper lighting at the plant leaf level. The CAD and STL files are available in the Appendix A folder.

This design is very simple, easily modified and therefore flexible with the overall goal to expose biological samples to simulated microgravity condition on the RPM with a simultaneous ground control under identical environmental conditions. By modifying the cassette, LED arrays, and/or the test tube racks, samples in other sized sample containers can be exposed to simulated microgravity environments with different lighting regimes. This design is suitable not only for plant research, but also for studies on organisms that have a unidirectional light requirement. This design can be adapted for other 3D clinostats which contain a power coupling/connector for external AC power sources on the rotation stage. For those clinostats without an on-stage power coupling, such as Gravite, a panel of batteries may be added to provide adequate power throughout the experiments.

B. 60mm² Petri Dish Removable Module (NTR: KSC-14337, Appendix B)

Depending upon the requirements of a simulated microgravity experiment, some designs can be very complex. A module with sample removal during rotation was developed to primarily support a plant circadian rhythm study shown in Figure 3. This module allows mounting 12 stacks of 4 x 60 mm² petri dishes at 60° intervals (48 in total) around a central vertical light core using the same broad spectrum Agrivolution white LEDs strips as shown in the previous petri plate design. The LEDs can be programmed for desired photoperiods and light intensities. Each stack of four petri dishes is mounted in a holder, which only opens to the central vertical light core and is held with low strength magnets (not shown in the diagram in Figure 3) to the

module frame. Therefore, each holder can be easily removed at various time points, without stopping the RPM rotation, thereby preventing interruption of the microgravity simulation on the other sample stacks throughout the experiment. The ground control rack each contains six stacks of four 60mm² petri dishes oriented for 1 g condition and LED strips mounted above the stack at the same distance. This module was designed particularly for experiments that need light exposure and can be modified for encompassing wavelengths from UV to far-red light with the addition of different LEDs. Experiment specific LED light stripes can be easily installed on the module. Two factors need to be considered by using this module: 1. Samples may experience minor jiggles during sample removal; and 2. Potential effect of the low strength magnets on both rotating and static samples, which may be minimal, but biological specimen dependent.

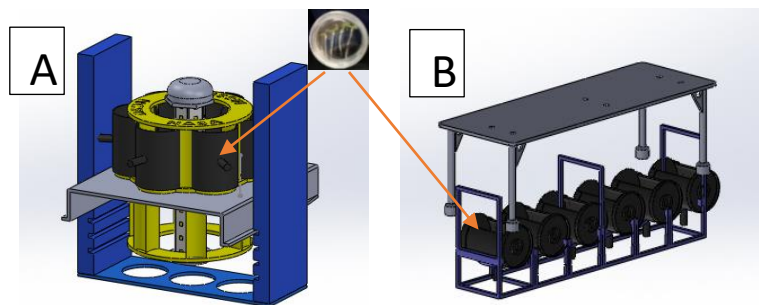


Figure 3: A) The inner rotating structure of the RPM showing 12 stacks of 4 x 60 mm² petri dishes equally arranged around a central core of LED light for biological samples e.g. small plants such as *Arabidopsis thaliana*. B) Associated ground control design showing the same 6 stacks of 4 petri plates oriented for unit 1 g and LED strips mounted above the stack. The CAD and STL files are provided in the Appendix B folder.

Regardless of the lighting conditions, this hardware has numerous possible applications for plant, cell and microorganism studies that require timed removal of samples, or a large “n” number within the same simulation run. Damping material or adaptors can be added to make sure the sample containers are secured or to accommodate samples in different sizes or numbers. The components of this module can be 3D printed or machine made with biocompatible materials from printable plastics, such as polylactic acid (PLA) or polyethylene terephthalate glycol (PETG), to aluminum.

C. Plant Growth Chamber (NTR: KSC-14335, Appendix C)

The module created for the RPM shown in Figure 4 is originally designed to support two sets of plant trays for microgreens, young plants, or any experiment that fits with the size of a 96 well plate (Zhang *et al*, 2021). The design is flexible and expandable to other size plant trays and only constrained by the sizes of the rotational axes of the RPM. White Agrivolution LED lights strips are powered as previously described and photoperiod adjustments possible, depending upon the requirements of the science investigation. The addition of a compact Arduino board allows controlling the LEDs timed power cycling, cameras, and various sensors. The chamber currently has two cameras mounted above the growth area on each side of the unit (top and bottom) to take time-lapse pictures of the subjects as the chamber is rotating. Latches were

designed to secure each tray/plate to the center plate. Suitable LED light strips with wavelength ranging from UV to Far red can be easily installed to this module. Therefore, this module can support a wide range of studies from plants, microorganisms, to cell cultures, with biological samples sitting at or near the center of rotation to minimize artifacts in microgravity simulations.

Additional adaptors can be added through holes on the sample plate or above the growth area to make sure various sample containers and experimental accessories are secured. There is plenty of space available for incorporating sensors for recording environmental data.

Modifications to this design can also be made to incorporate larger growing plants, but the plant tray would only be able to have plants growing on one side due to the size limitations within the rotating ring structures of the RPM. For the fixture to contain larger plants, improvements including active watering systems are highly recommended to compensate for the increased water demand. Furthermore, considerations on potential rotational artefacts are needed for growing larger size plants out of the center of rotation axes. The components of this module can be 3D printed or machine made with biocompatible materials from printable plastics to aluminum.

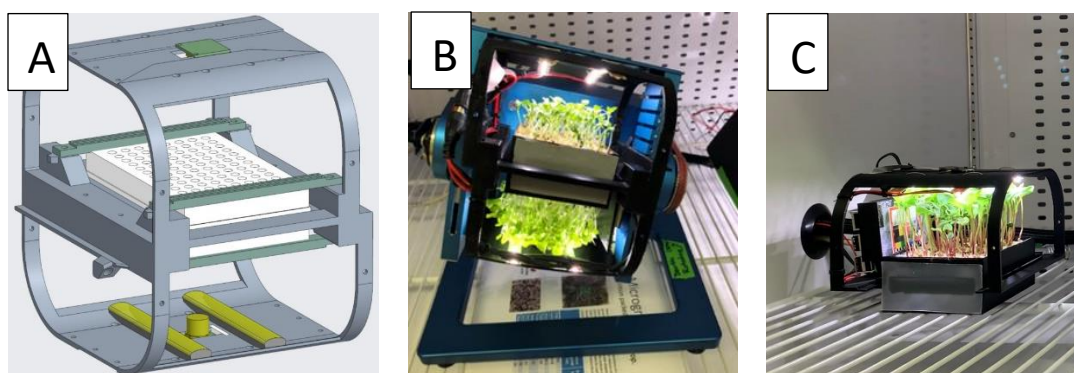


Figure 4: A) Drawing of the Microgreen Plant Growth Chamber which slides into the mountings on the inner ring of the RPM. The area for growth represents the area equivalent to a 96 well plate (shown for size comparison). The CAD and STL files are available under the Appendix C: Plant Growth Chamber folder. B) Plant growth can occur from both sides as the frames are rotating. C) Static control setup to expose plants to the same environmental conditions.

D. 50ml Tube Holders (NTR: KSC-14336, Appendix D)

These holders were originally developed for holding 50 ml conical tubes containing biofilm coupon experiments for comparative studies of both the RPM (Figure 5A) and 3D clinostat (Gravite) (Figure 5B) studies. The RPM holder can hold 9 x 50ml conical tubes. The design parameters arrange the position of tubes by equalizing and minimizing the distances tubes would be away from the center of rotation, and thereby minimizing variations and centrifugal forces associated with rotating the samples. The module has two side bars to slide into the inner rotating ring of the RPM and be attached using screws to the preset holes on the inner ring. The Gravite unit can hold 10 x 50 ml conical tubes (5 units on each side of the rotating

central axis). They mount directly to the removable baseplates supplied by the vendor. An additional holder was designed to fit onto the RCC systems and potentially other 2D clinostats currently available in the MSSF. Figure 5C shows a modified 50ml tube holder for a RCC system. These units can be easily adapted or adjusted to fit other containers and other types of science. Damping material or adaptors can be added to make sure the tubes are secured or to accommodate tubes in different sizes. These holders can be 3D printed or machine made with materials from plastic to alumina. Potential applications include studies on biofilm, agar or liquid based microbial cultures, cell cultures, plants, invertebrate animals, and fruit fly and other insects.

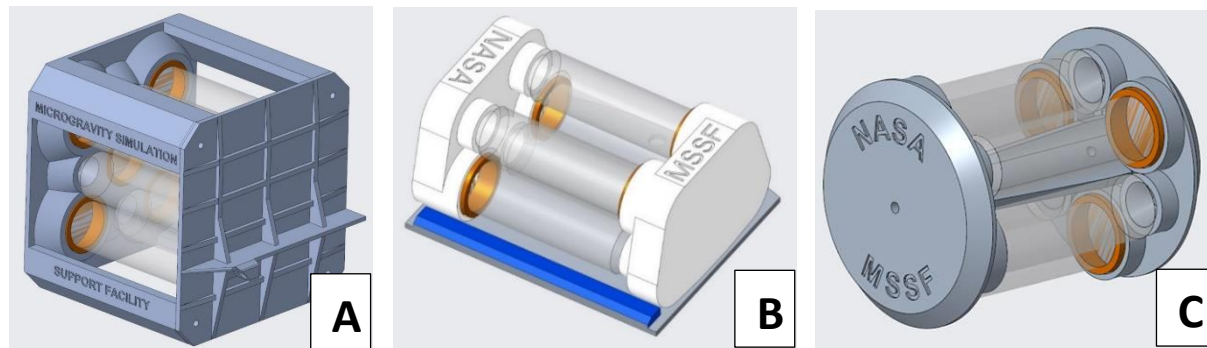


Figure 5: A) The 9 x 50 ml tube holder designed for biofilm coupon experiments on an RPM; B) The tube holder for a Gravite unit (only one side represented in this image as two identical units can be mounted on the inner rotational base); and C) The tube holder for an RCC/2D clinostat. The CAD and STL files of these designs are available under the Appendix D folder.

E. Live Cell Imager Module (NTR: KSC-14221, Appendix E)

We have successfully developed and demonstrated, for the first time, a novel module that is suitable for real-time bright-field and fluorescence microscopic imaging of living organisms undergoing microgravity simulation on a desktop RPM (Figure 6A). The module was validated in microgravity simulation conditions with living mammalian cell samples, and time-lapse footage was obtained for experiments lasting up to 80 h. The stability of the system during mechanical disturbances was enhanced using post-processing algorithms. Our results highlight the potential application of real-time microscopic observation and imaging in microgravity simulation devices to study the impact of altered gravity on cellular and subcellular processes. Detailed information is available in our recent publication (Neelam *et al*, 2021).

There remains notable areas of improvement for the present design of the microscopy system and microgravity simulation experiments. A four-leg microscope holder module (Figure 6C) designed for the RPM performed better at reducing vibration with improved image stability compared to the 2-leg holder version (Figure 6A). In spite of the improvement, analysis of the 4-leg scope holder still found residual movements suggesting the junction of the sample slide with the 3D printed microscope holder, which is connected with the RPM frame, may have minor perceptible movement at the micron scale (Zhang *et al*, 2021). In addition, the current module is designed to accommodate adherent cell samples seeded in channel slides and slide flasks. To allow for greater versatility of the module, the sample holder stage component will be

modified to enable observations of other biological specimens, such as plant seed/seedling specimens, on microgravity simulation devices. Furthermore, without rotation, the static control unit may experience some heat accumulation issues, especially in a 37°C incubator, which may require a mini fan to improve the air circulation.

This module can be easily adapted to fit other 2D or 3D clinostats, however, on-stage power supply is required for prolonged image acquisition. The components can be 3D printed or machine made with light-weight compatible materials. High rigidity materials may be required to better maintain the stability while rotation. Furthermore, the counterbalance may need to be adjusted based on mass changes to make sure the mass center is at the center of the two rotation axes.

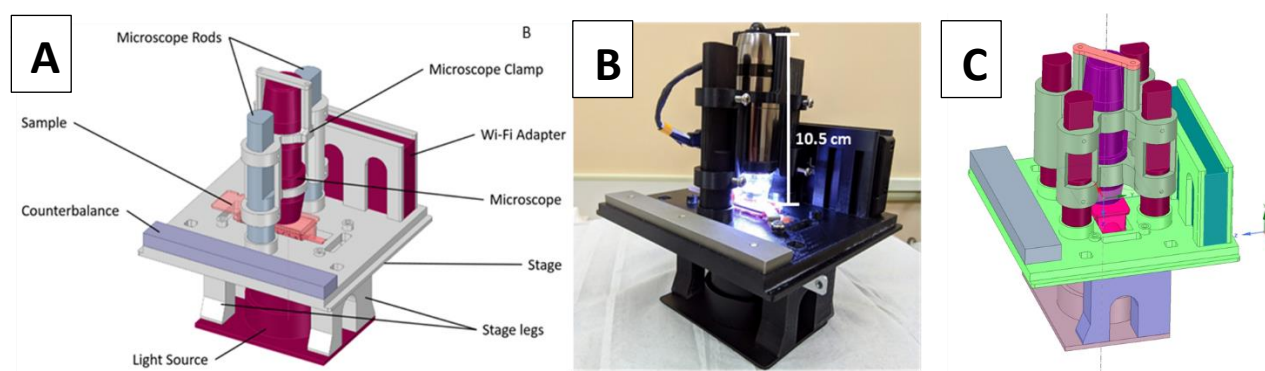


Figure 6. CAD rendering of the assembled module and microscopy system. A) Components of the live microscopic imaging module for RPM. The module is modified to accommodate samples contained in the μ -slides and SlideFlasks. The CAD and STL files are available under the Appendix E: Live Cell Imager Module folder. B) A 3D-printed module integrated with the microscopy system. C) The quadripod design with improved stability.

F. Other Accessories (Appendix F)

Base Centering Plate: This is a base centering plate developed for RPM to place samples at both sides of the plate to be at the closest position to the center of the two axes. The base centering plate can include holes with latches or hooks to hold rubber bands to secure sample containers.

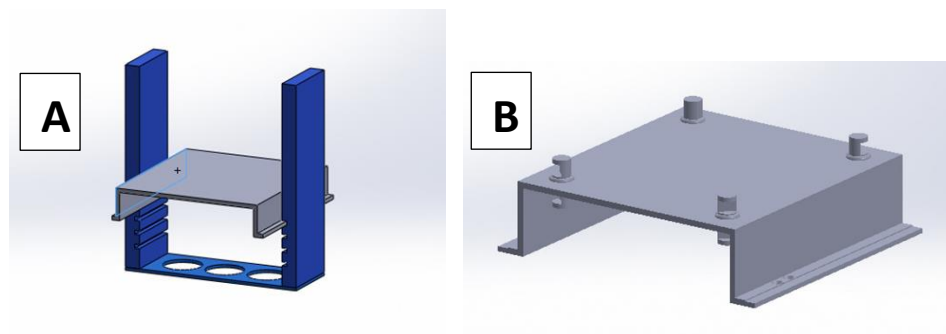


Figure 7. A) Base Centering Plate design for RPM. The CAD and STL files are under the Appendix F: Base Centering Plate folder. B) Base Centering Plate design with hooks.

High Aspect Ratio Vessel (HARV) Holder: The HARV holders were developed for the RPM and Gravite 3D clinostat to hold HARV vessels (Synthecon, TX). Modifications of the HARV vessels may be required based on the science requirements. The holders can support two 50 ml HARV vessels (Figure 8A), eight 10 ml vessels (Figure 8B), or a combination (Figure 8C). This holder can be 3D printed or machine made with biocompatible materials from plastic to alumina, for disposable and autoclavable vessels, respectively.

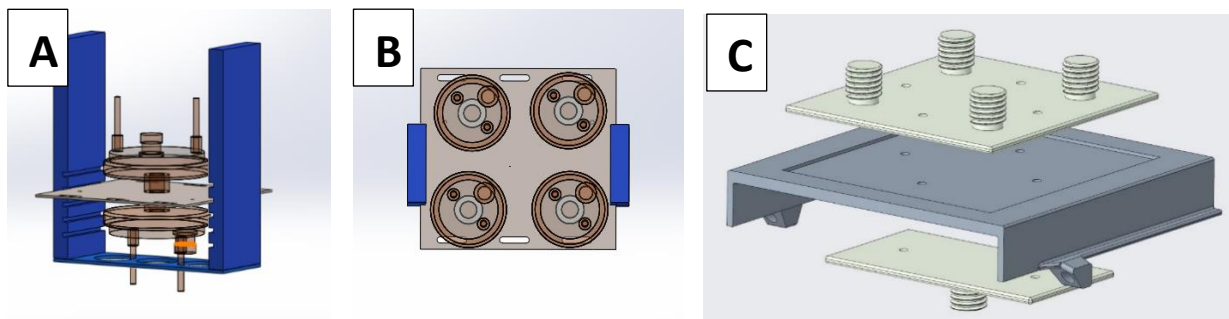


Figure 8. HARV accessory Holder. A) Holder for two 50 ml HARV vessels. B) Holder for eight 10 ml vessels. C) Holder for a combination of 10 ml and 50 ml vessels. The CAD and STL files are provided in the Appendix F: HARV Holders folder.

Rubber Band Puller: This simple rubber band puller can be used for both the RPM and Gravite whenever rubber bands are used to secure sample containers. This simple design allows easier and faster sample removal. It can be easily redesigned and quickly 3D printed to support multiple sample types and sizes.

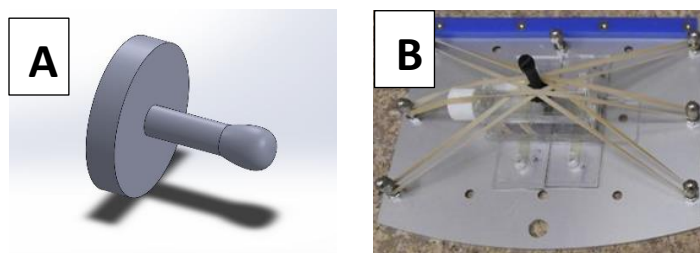


Figure 9. A) Rubber band puller design. The STL file is available under the Appendix F: Rubber Band Puller folder. B) Depiction of how it aids in holding items down onto a Gravite baseplate.

4.0 Conclusion

In this package, we include a variety of customized and specialized science carrier modules and several accessories developed by the MSSF team to enable a broader range of microgravity research using microgravity simulation devices. The goal of this package is to share what we have learned from the manufacturers and investigators in the ground microgravity simulation

area and to equip the space biology science community with new tools to use microgravity simulation devices more effectively.

5.0 Acknowledgements

We really appreciate the administrative support from Dr. Howard G. Levine and Dinah I. Dimapilis, and the lab support from Anna Maria J. Ruby. We also thank the help from Michael A. Lane from the KSC Prototype Shop, and Tonia Tsinman, a student intern, for their valuable suggestions on hardware design and material selection, especially for the microscope module. This package includes works performed by the following development teams:

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6. Accessories. Torres J, Richards J, Gleeson J, Neelam S, Udave C, Zhang Y.

6.0 References:

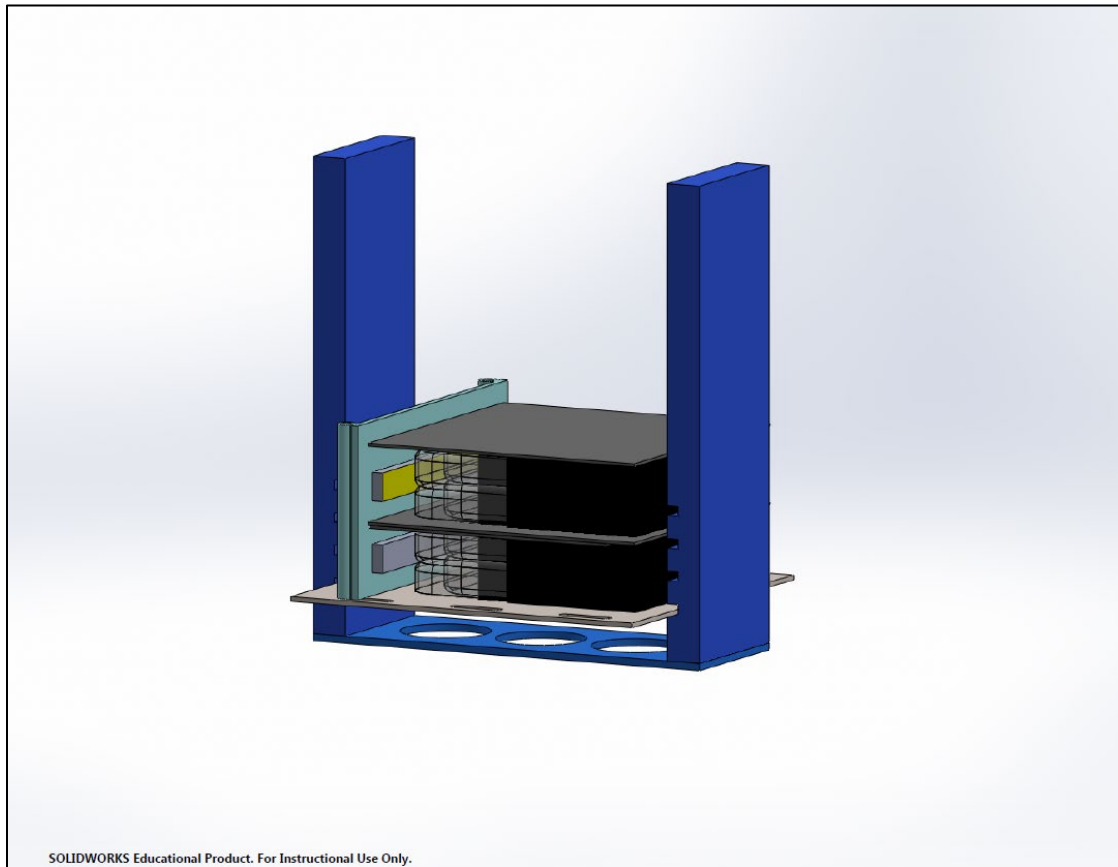
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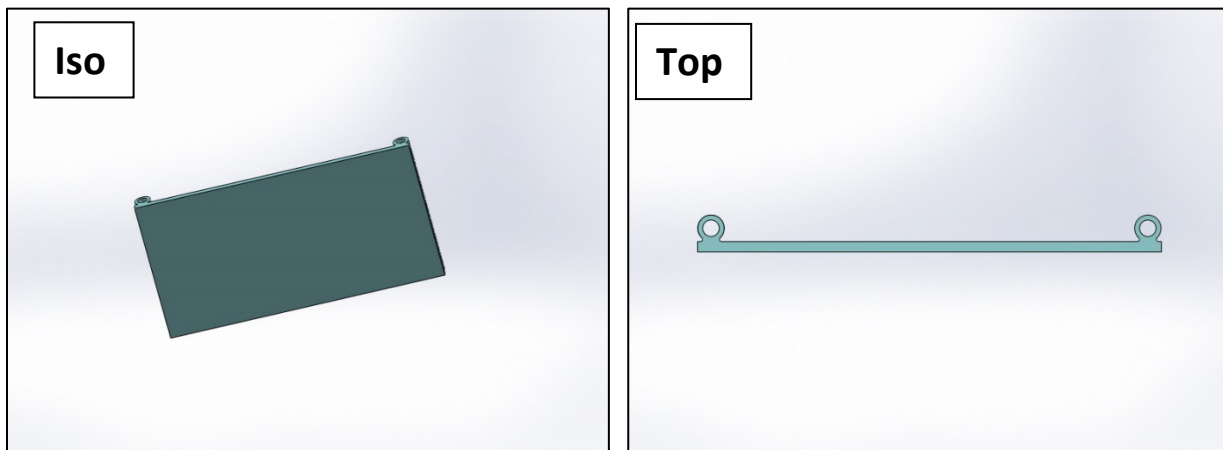
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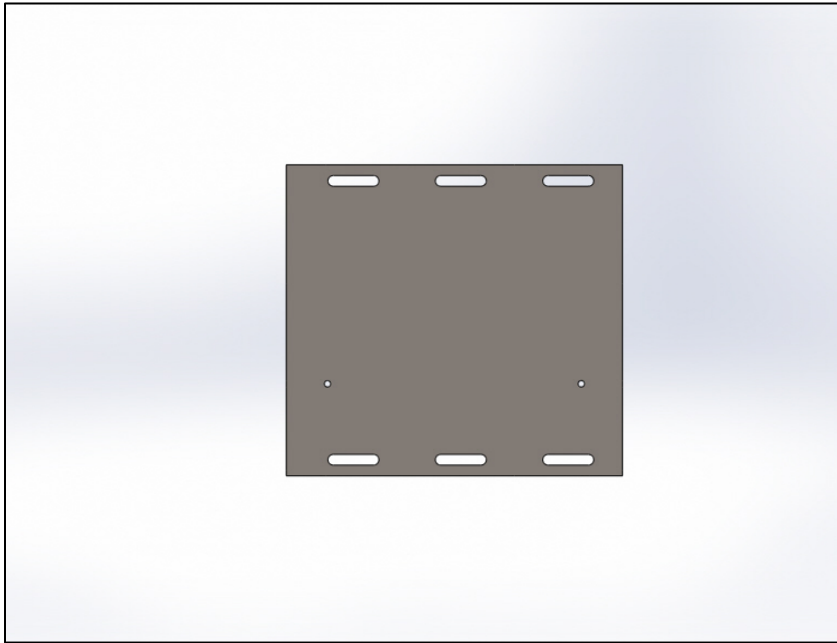
A. CAD Design.



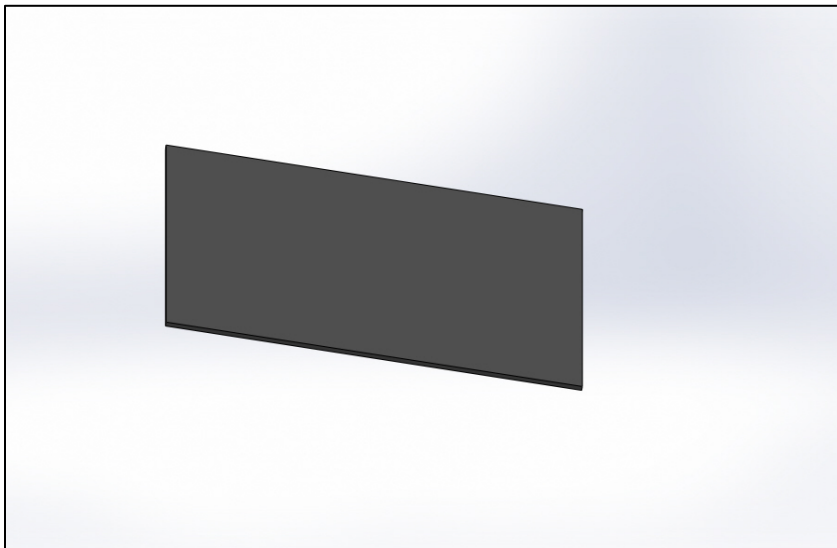
B. Light Mount.



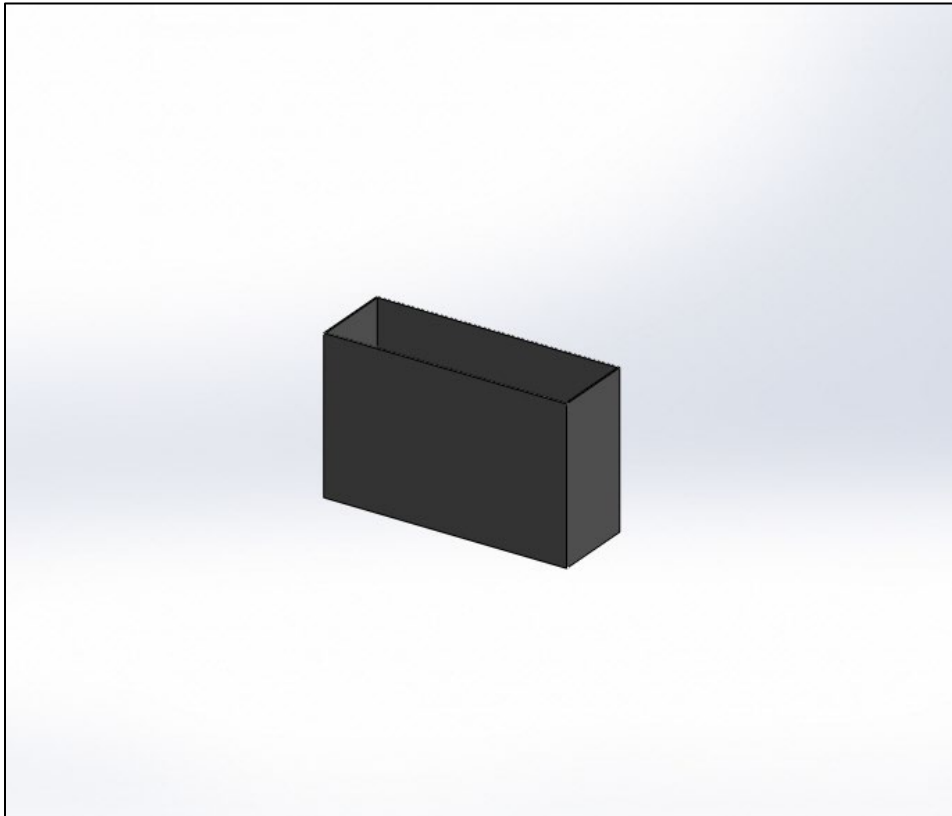
C. RPM Base Plate.



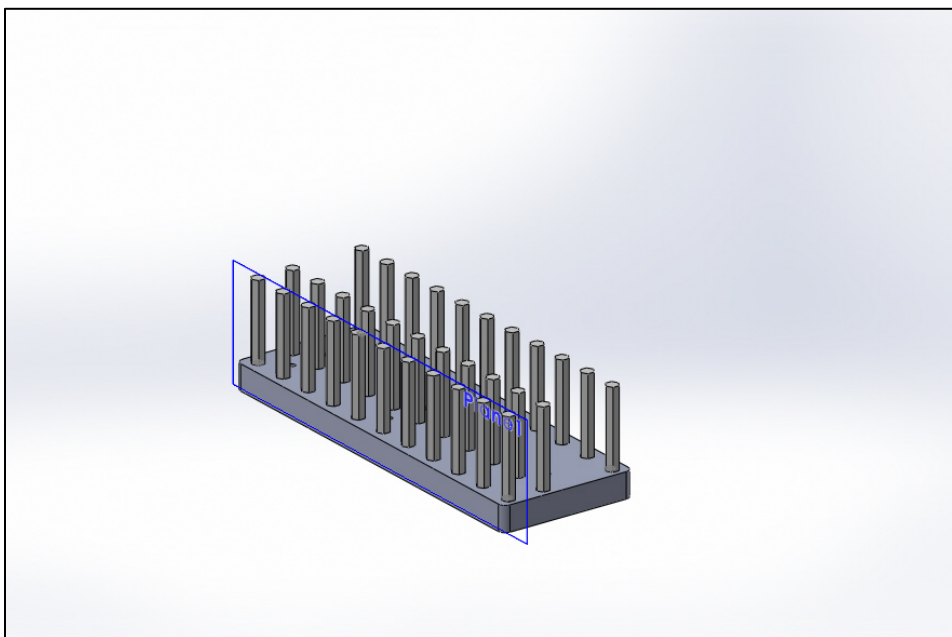
D. Opaque Plate Cover.



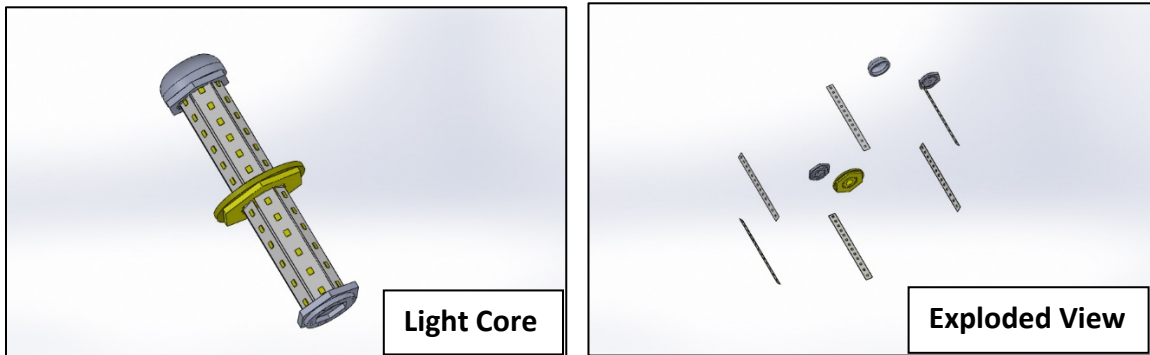
E. Plate Sleeve.



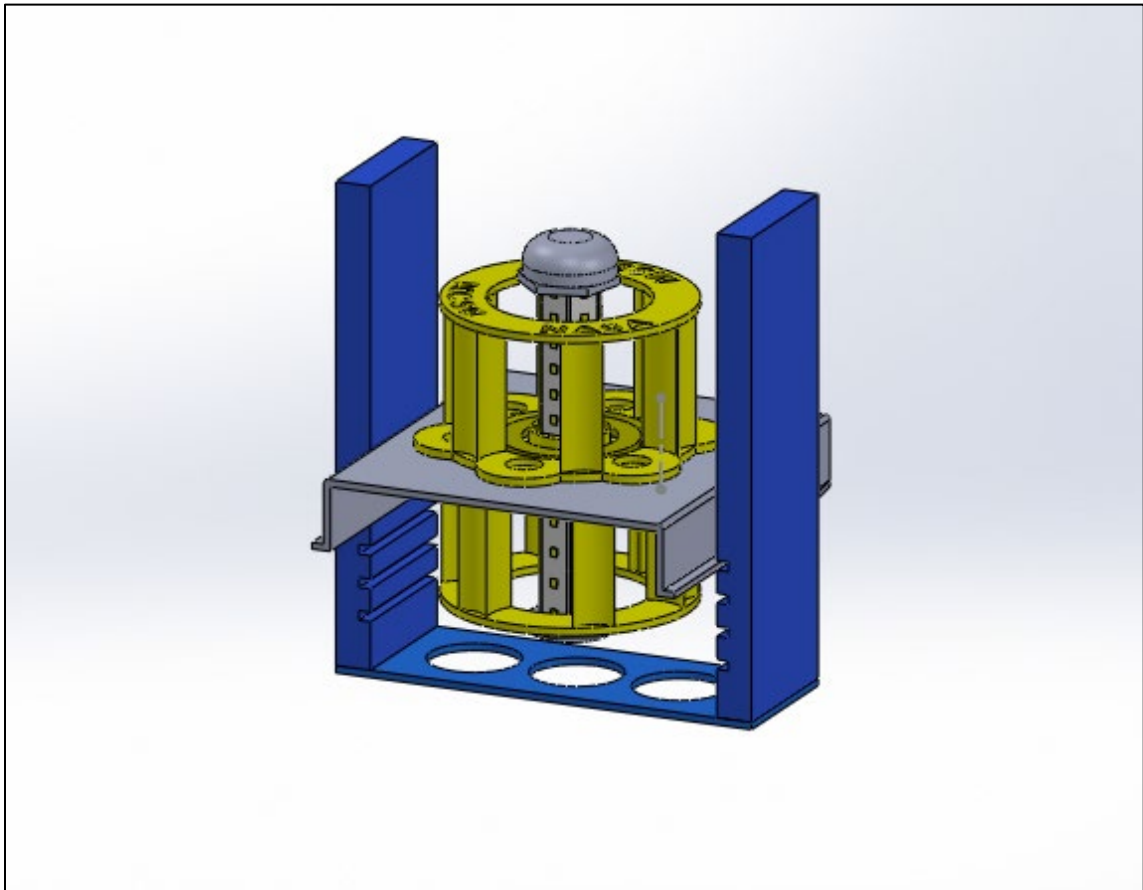
F. Modified Plate Holder.



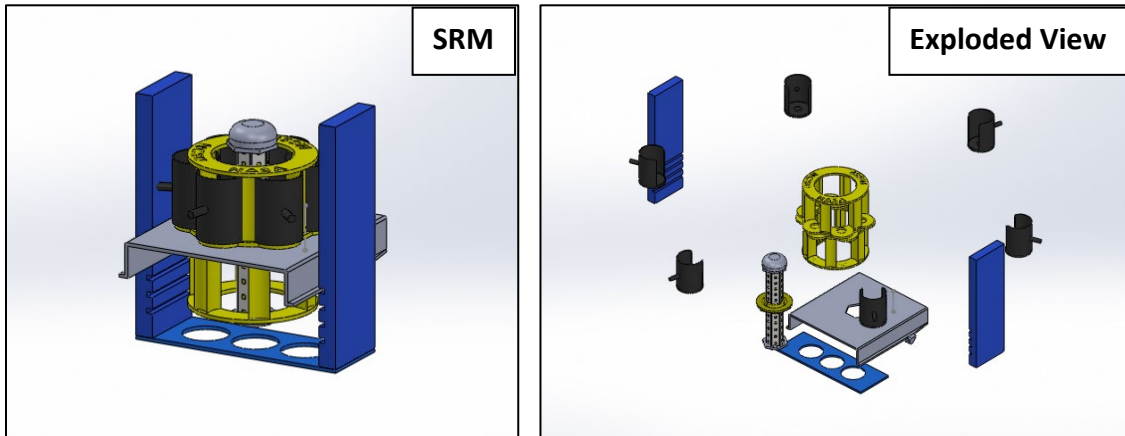
A. 360° Plant Growth LED Bulb DQM and the Exploded View.



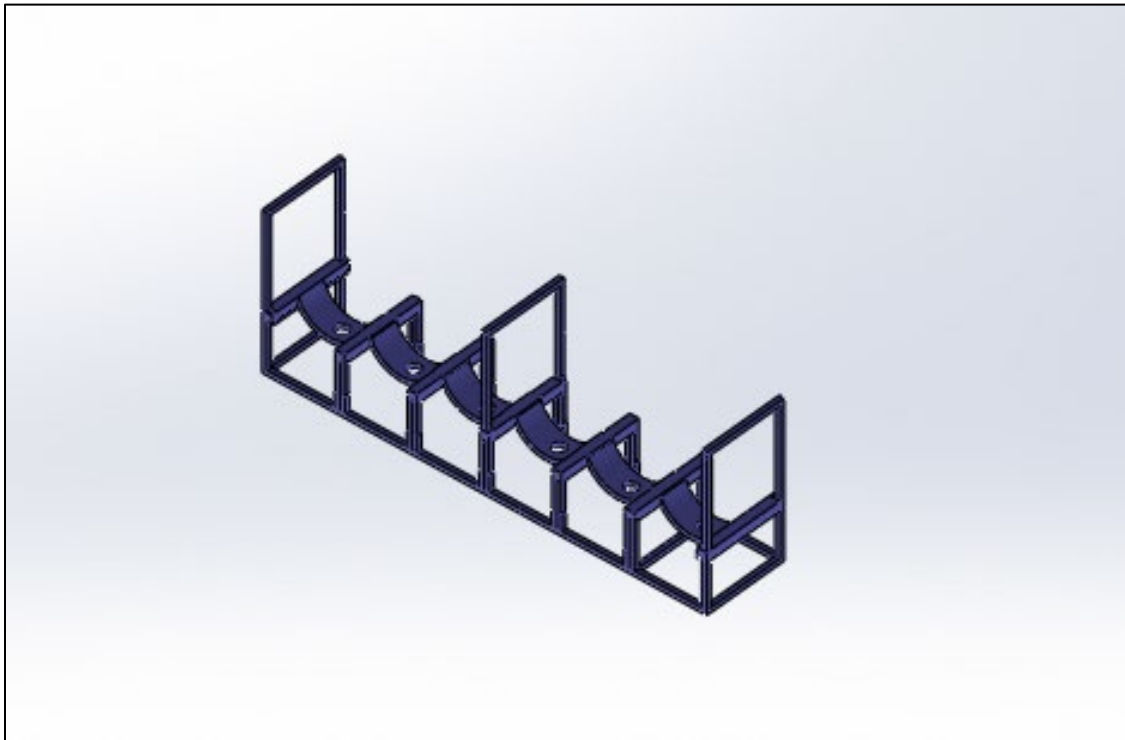
B. Sample Removable Module (SRM).



C. Sample Removable Module with Samples and the Exploded View.

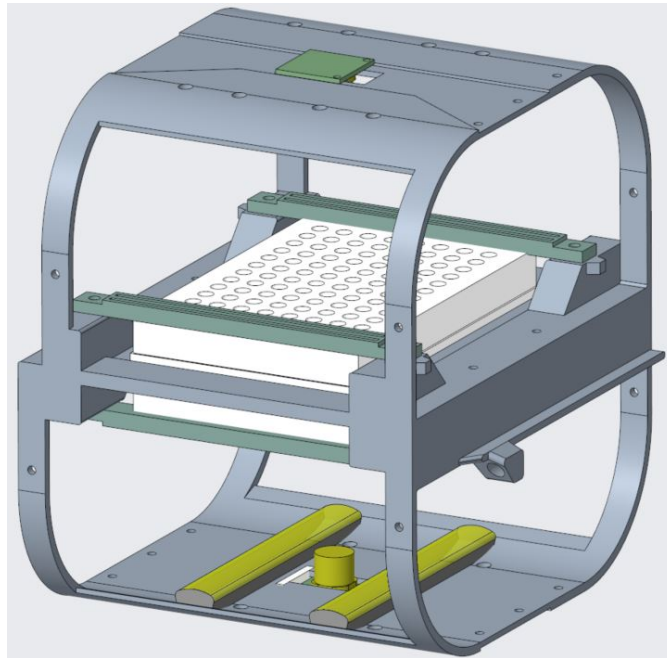


D. Cradle Static 10mm Sample Tray.



15 | Page
PLANT GROWTH CHAMBER INFORMATION

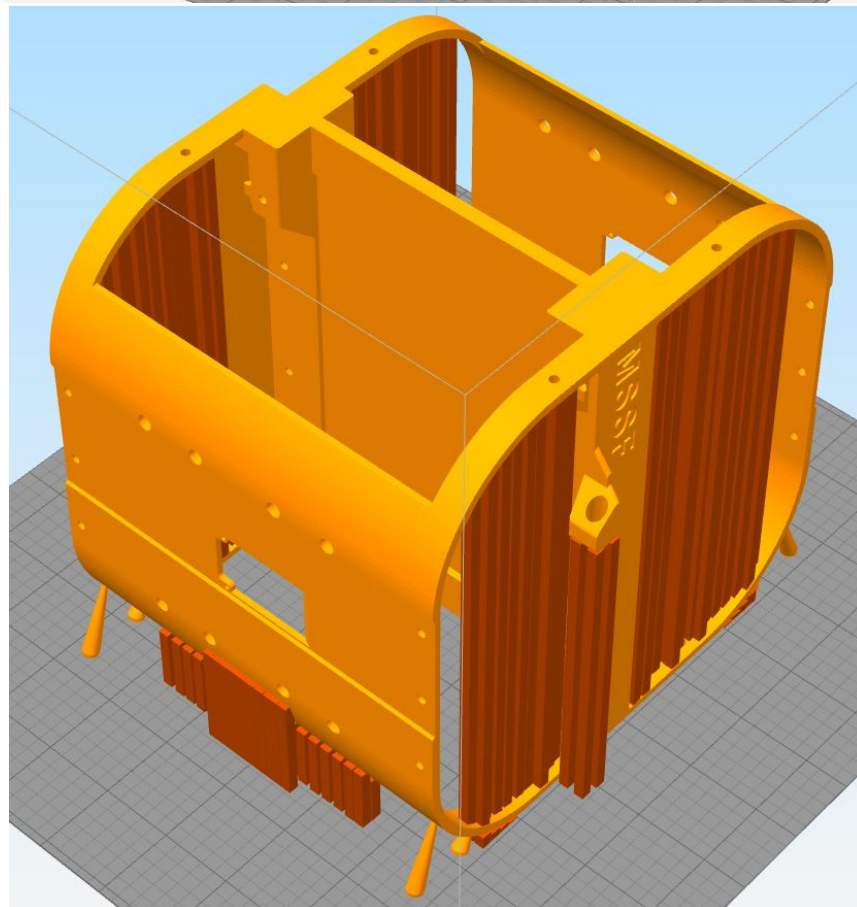
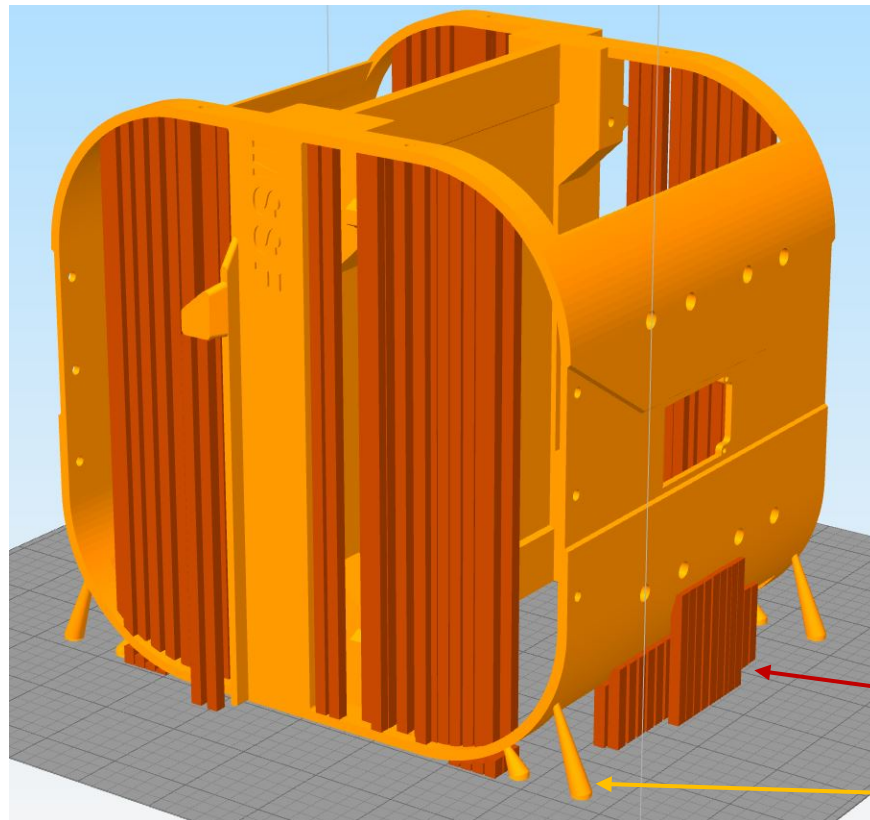
The Growth Chamber's center surface is in line with the RPM's center of rotation. The double-sided surface allows two growth plates to be mounted to it. Latches fastened in place or rubber bands can hold the plates in position. The structure's "ceilings" have mounting holes for LED strips and a small camera. There are additional mounting holes along the sides of the structure that can be used to mount control boards, sensors, etc. 3D printed holes can be self-threaded by screws as needed. The design utilizes most of the RPM's usable volume so any additions should stay within the structure's boundaries as to not interfere with the RPM's rotation. The inset area seen on the upper left side of the image below is there give clearance to the large cable on the RPM when the structure is being slid into place.



The structure can be 3D printed in one piece, however it may be too complicated for less advanced 3D printers. The support arches can be a source of issues while printing. It is suggested to use a lower printing temperature and a high fan setting to avoid the curved arches from curling upwards as they cool.

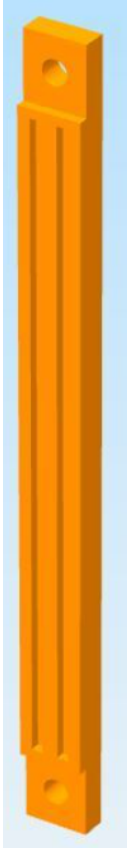
Support structures are strongly recommended. In the images below, the red pillars indicate good locations for supports. These will help with printing the overhangs and will help stabilize the otherwise flimsy print while it is printing. A higher infill percentage is also recommended since there are many thin features that could be fragile. The images below also illustrate the suggested print orientation. One version of the CAD model includes modeled-in conical supports (in orange) connected to the lower curved arches as seen at the bottom of the two images below. These cone supports help keep the "ceilings" from shaking during printing. After printing is complete, they can be cut off of the structure.

Screenshots for 3-D Printed Parts

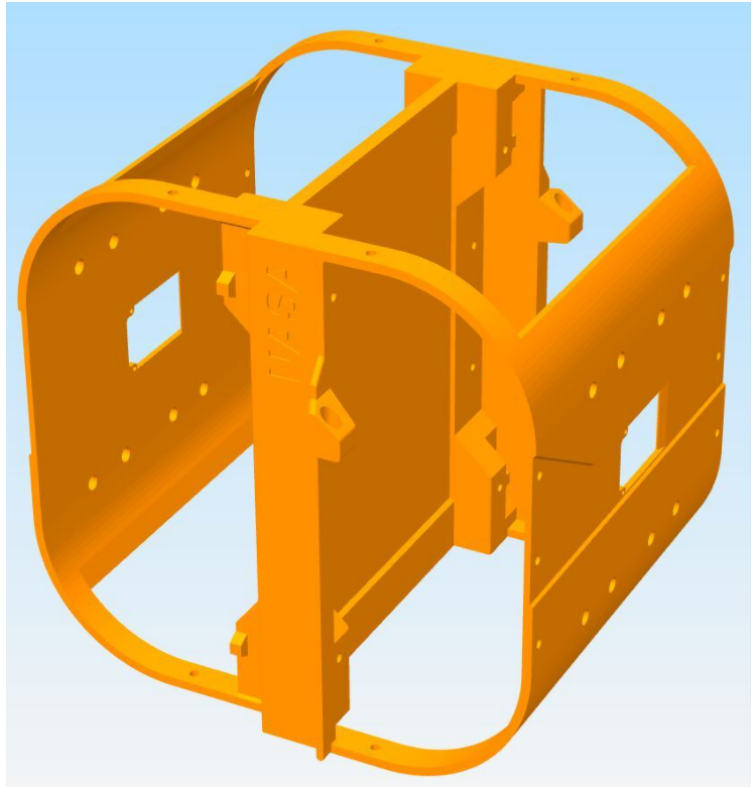


Generated Supports

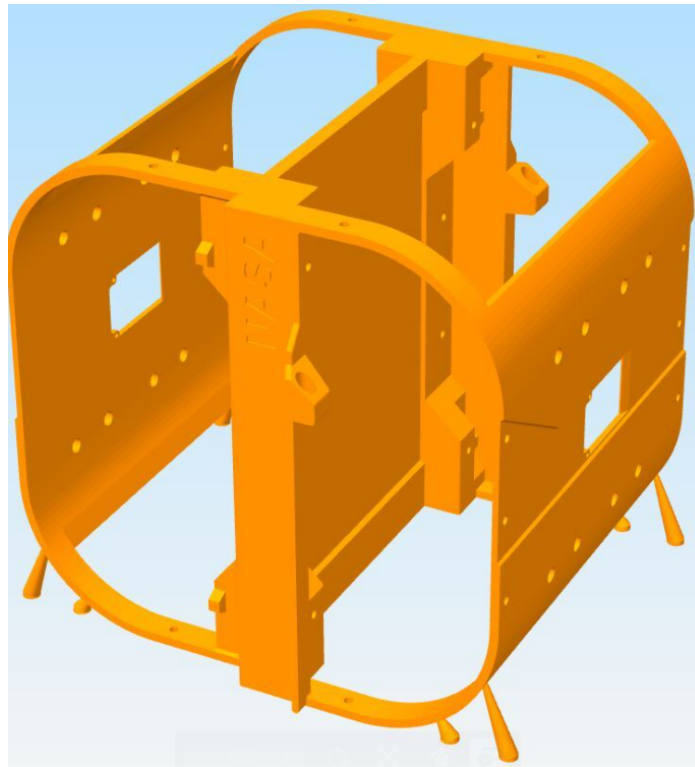
Optional Modeled-In
Supports



C Plate_Latch.JPG



C GC structure.JPG



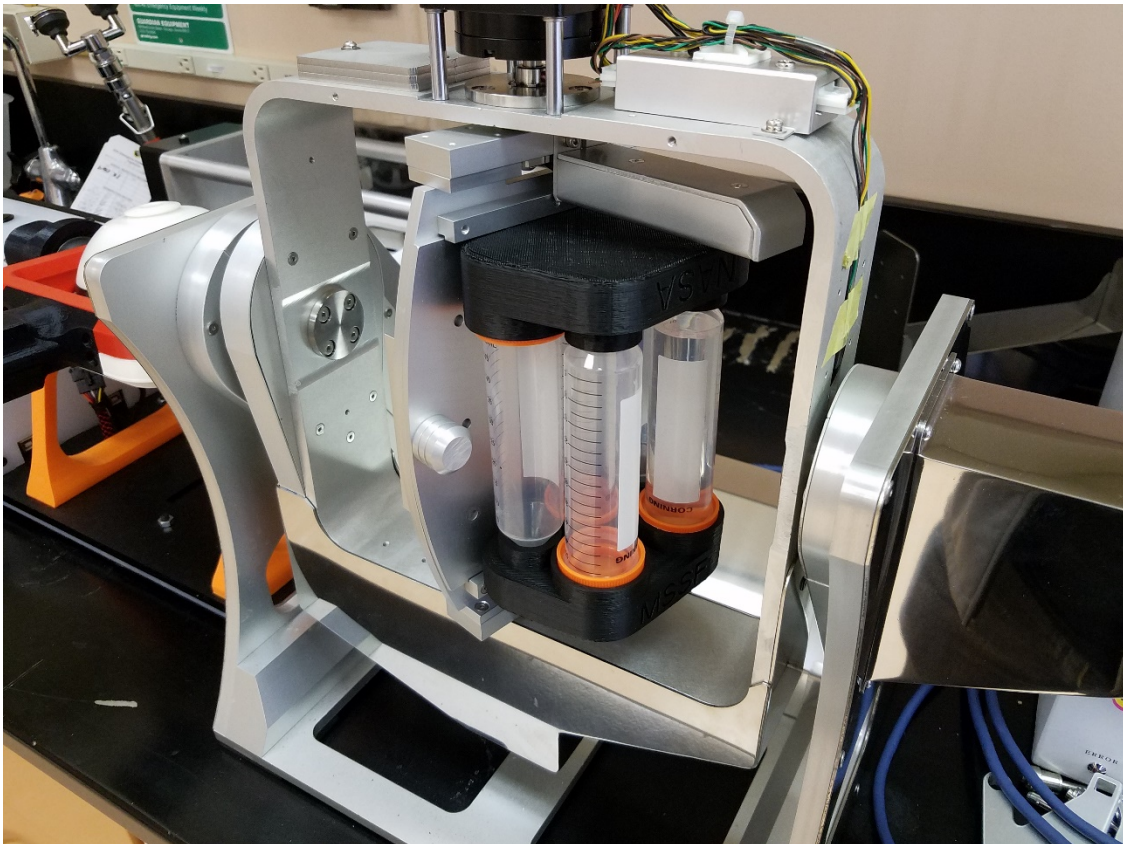
C GC structure_support.JPG

APPENDIX D: TUBE HOLDER INFORMATION

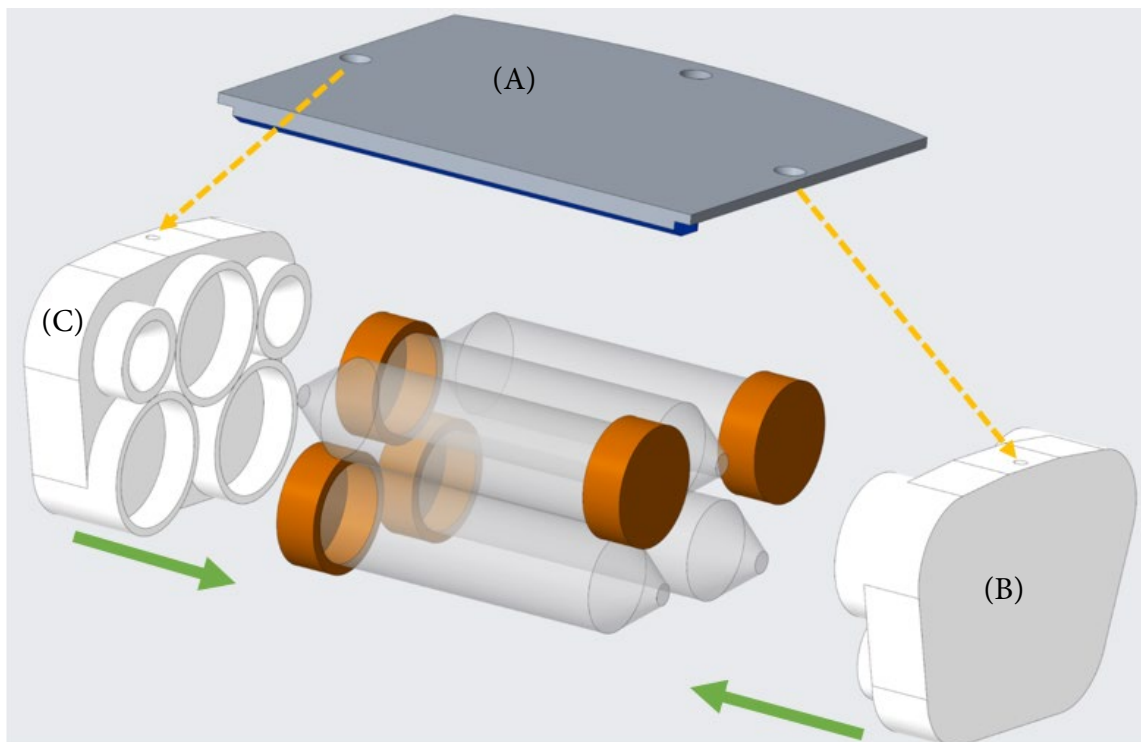
GRAVITE TUBE HOLDER INFORMATION

This design holds five 50ml tubes each and two can be mounted to the Gravite for a total of ten tubes. The picture below shows one mounted to one side of the Gravite. Each part holds the tubes by their caps via a press-fit indent for each tube. Thin strips of tape can be added to the inner diameter of the indents for the caps in order to make it a tighter fit if the tubes are loose. Each part mounts to the plate via one flathead screw which can self-thread into the 3D printed plastic. This plate slides onto the Gravite and is secured by one thumb screw.

The image on the next page illustrates the best way to load the tubes. One half should be mounted to the plate. Two tubes should be fit into one half and three tubes fitted into the other half. The unfastened half should then be flipped upside down and fitted into place above the other half and fastened via one screw to the plate. This will sandwich the five tubes between the two halves. The same can be done again to another plate which can then slide onto the other side of the Gravite.



APPENDIX D: TUBE HOLDER INFORMATION



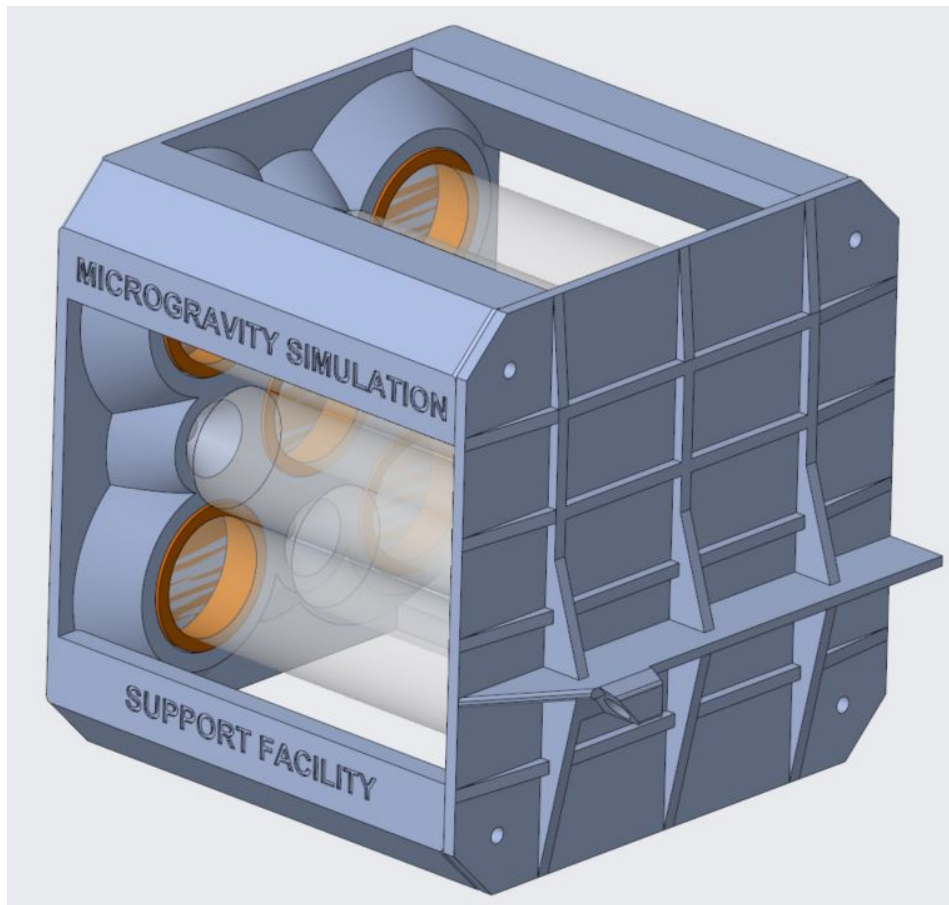
APPENDIX D: TUBE HOLDER INFORMATION

RPM TUBE HOLDER INFORMATION

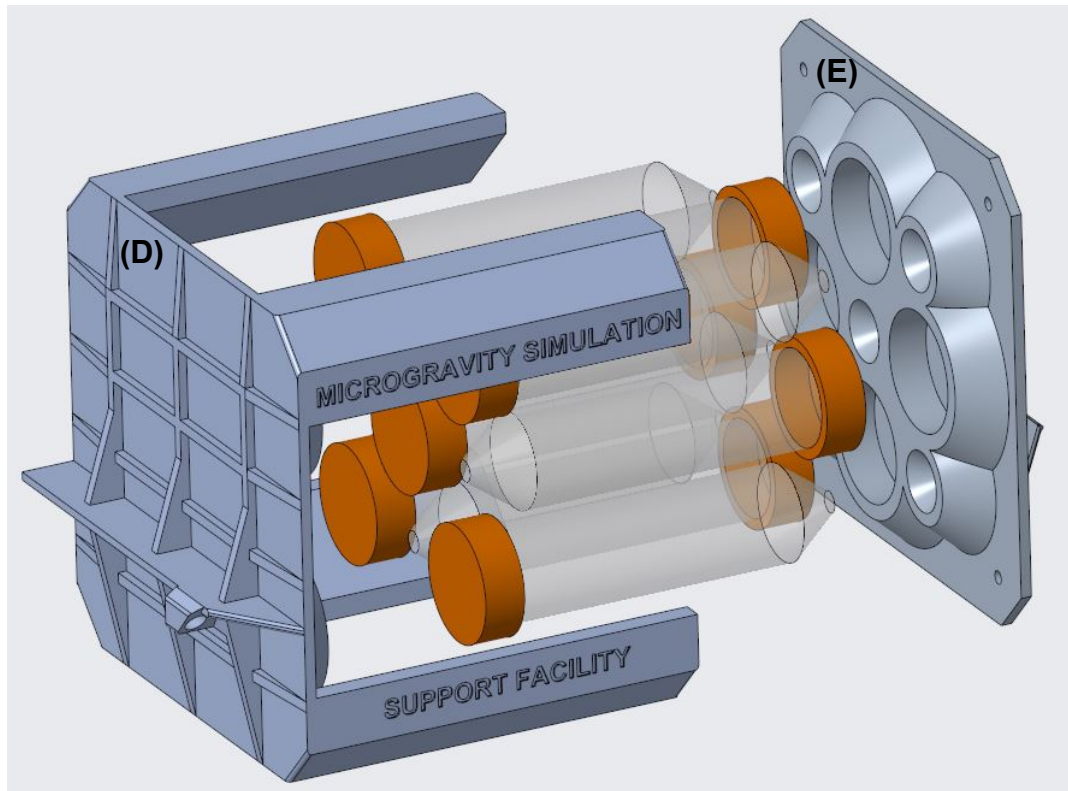
This design consists of two parts and holds nine 50ml tubes. It can be slid onto and fastened to the RPM via the side rails. Each half holds the tubes by their caps via a press-fit indent for each tube. Thin strips of tape can be added to the inner diameter of the indents for the caps in order to make it a tighter fit if the tubes are loose.

The image on the next page illustrates the best way to load the tubes. Four tubes should be fit into one half and five tubes fitted into the other half. One half should then be flipped upside down and fitted into place above the other half and fastened via four #8 screws at the corners. This will sandwich the nine tubes between the two halves. The threaded holes can be self-threaded by the screws if the structure is 3D printed.

The images on the last page illustrate the suggested orientation and ideal locations for supports when 3D printing this structure's parts. The red columns indicate the support locations which will stabilize the print and support the overhangs. To be printed successfully, the upper two large arms of the design especially need supports.



APPENDIX D: TUBE HOLDER INFORMATION

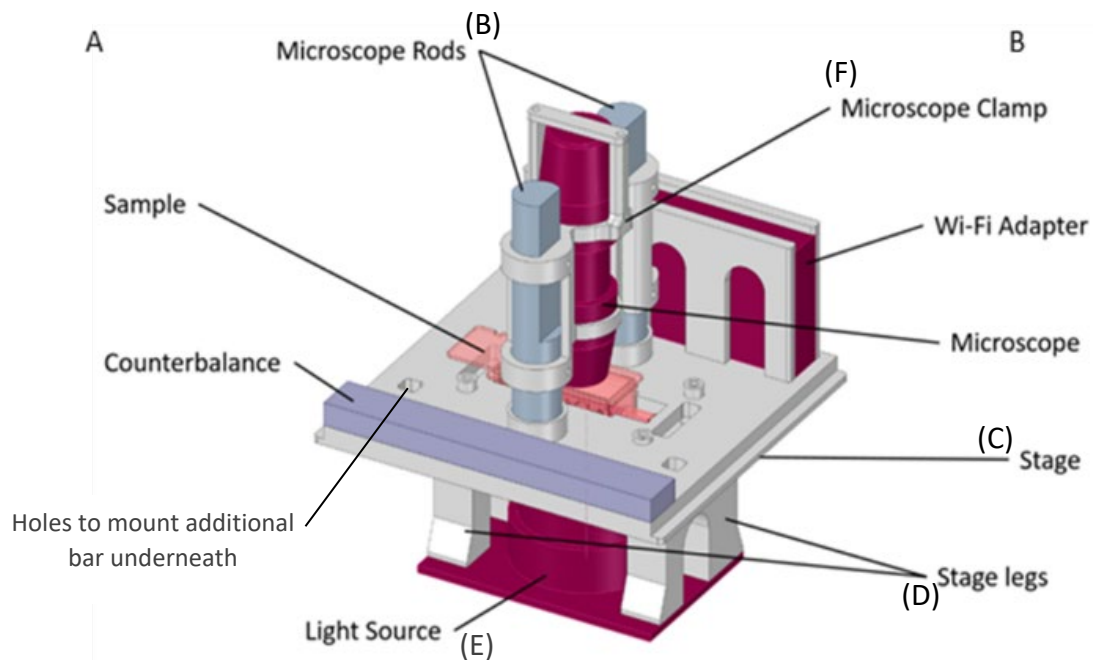


LIVE CELL IMAGER MODULE INFORMATION

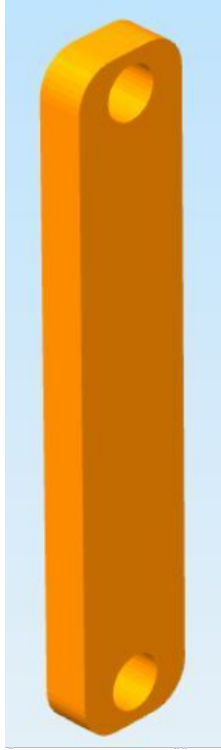
This system is designed to hold an imaging microscope over a sample holder. The microscope slides into the mount and a latch on top holds the microscope in place. A set screw can also be tightened against the microscope to further secure it. The microscope mount then slides onto the rods. When at the appropriate height, the 4 set screws should be tightened onto the rods to hold the mount in place. A light source can be mounted below the sample to backlight it.

If 3D printed, the threaded holes in the design can be self-threaded by the screws. For stability and strength, a higher infill percentage is recommended for the printed microscope mount. Supports will also be required to 3D print the mount.

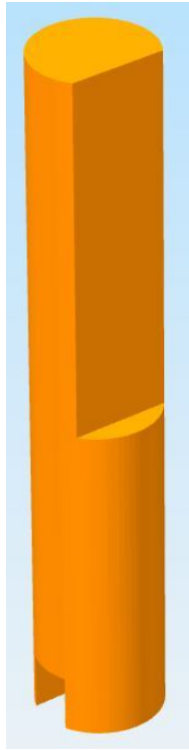
To fasten to the RPM, an additional bar needs to be fastened just below the side rails of the structure. That bar can then be fastened to the RPM's M3 threaded holes.



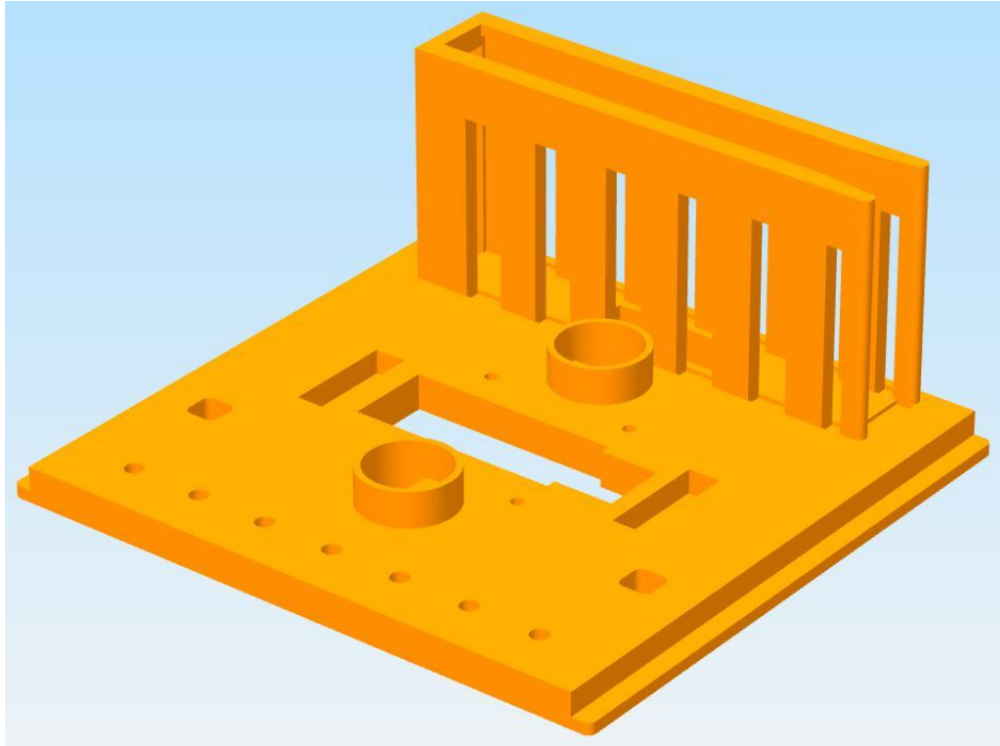
Screenshots for 3-D Printed Parts



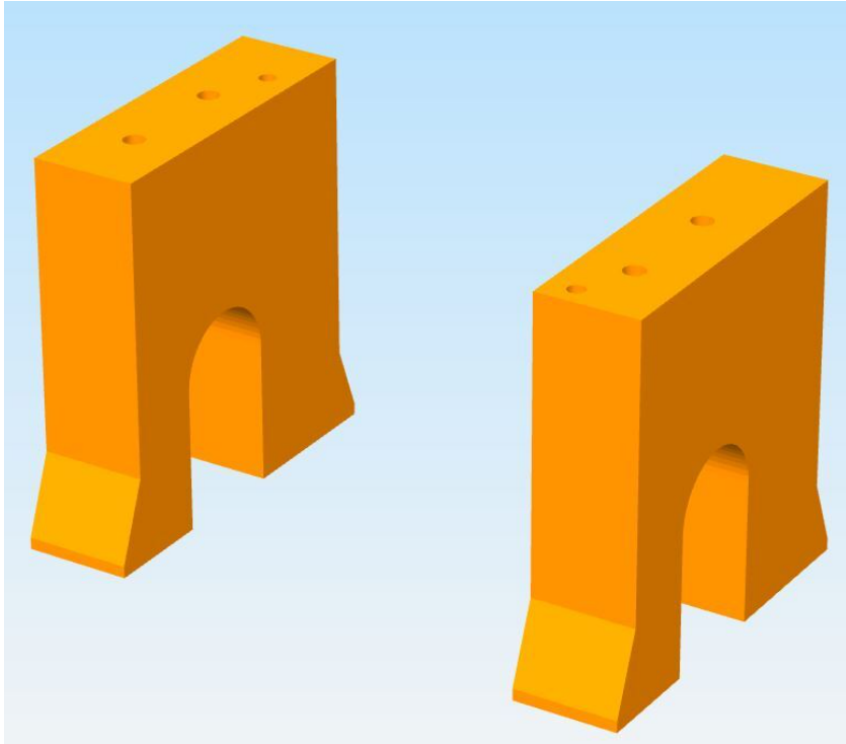
(A) E scope_holdbar.JPG



(B) E scope_rod.JPG



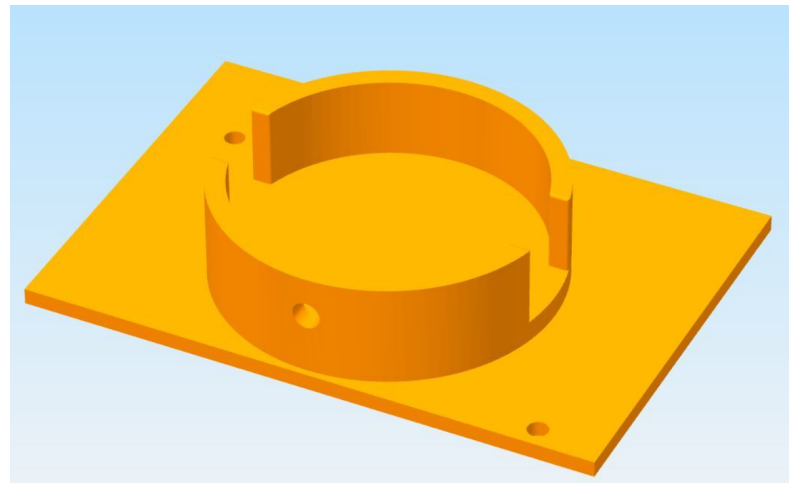
(C) E holder_base.JPG



(D) E holder_legs.JPG



(F) E scope_holder.JPG

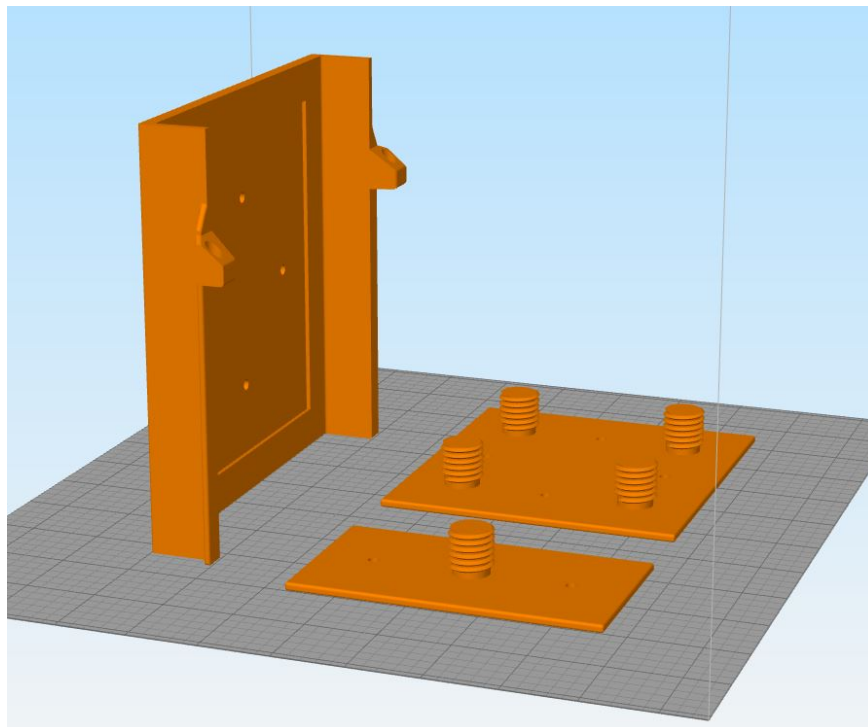
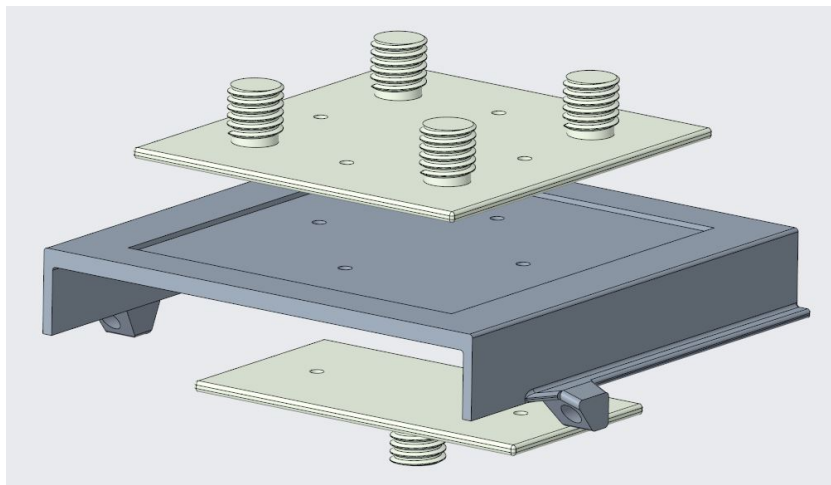


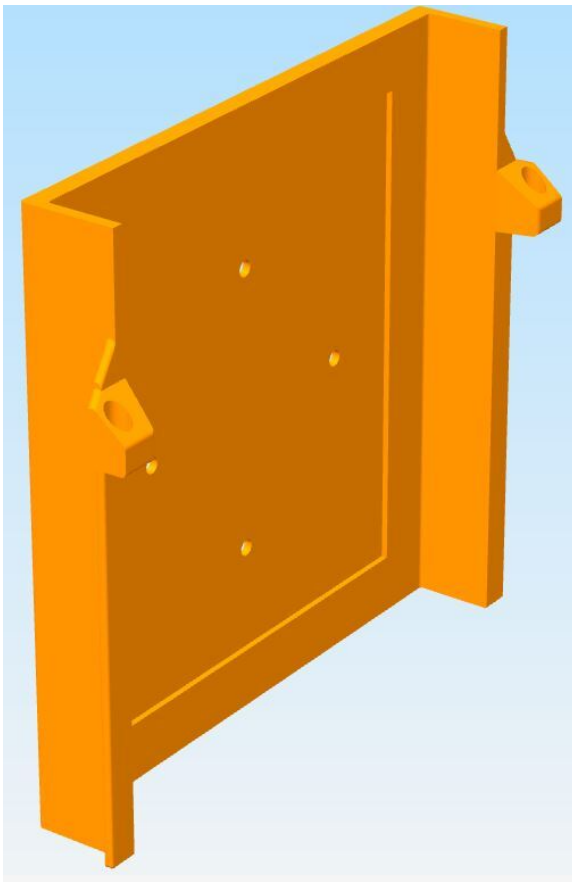
(E) E light_holder.JPG

APPENDIX F: HARV HOLDER

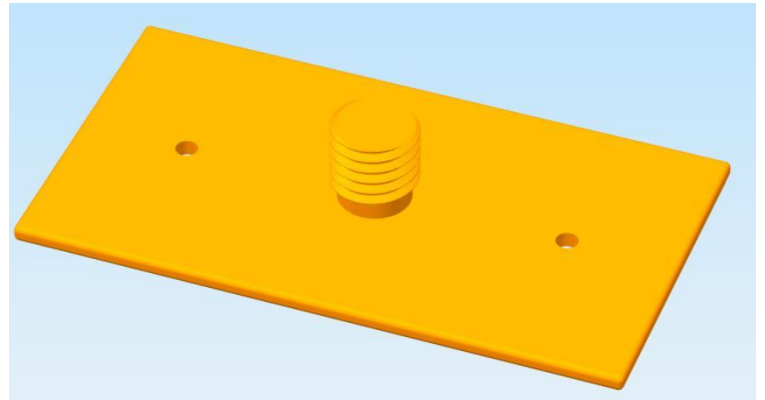
This design consists of a base that can slide and fasten onto the RPM and two plates with threaded rods on them. The plates can mount to both sides and either have four threaded rods on it for the smaller HARV's or one single threaded rod for the larger HARV. The threads match those found on the bottom of the HARV's. The plates are fastened to the base by at least 2 screws and nuts. The plates (without the base) can also be used on the Gravite with the use of rubber bands and tape.

The base and the threaded plates do not need supports if 3D printed in the orientation seen in the lower image. The plate threads will print best in this orientation. A high layer resolution is recommended for better quality threads.

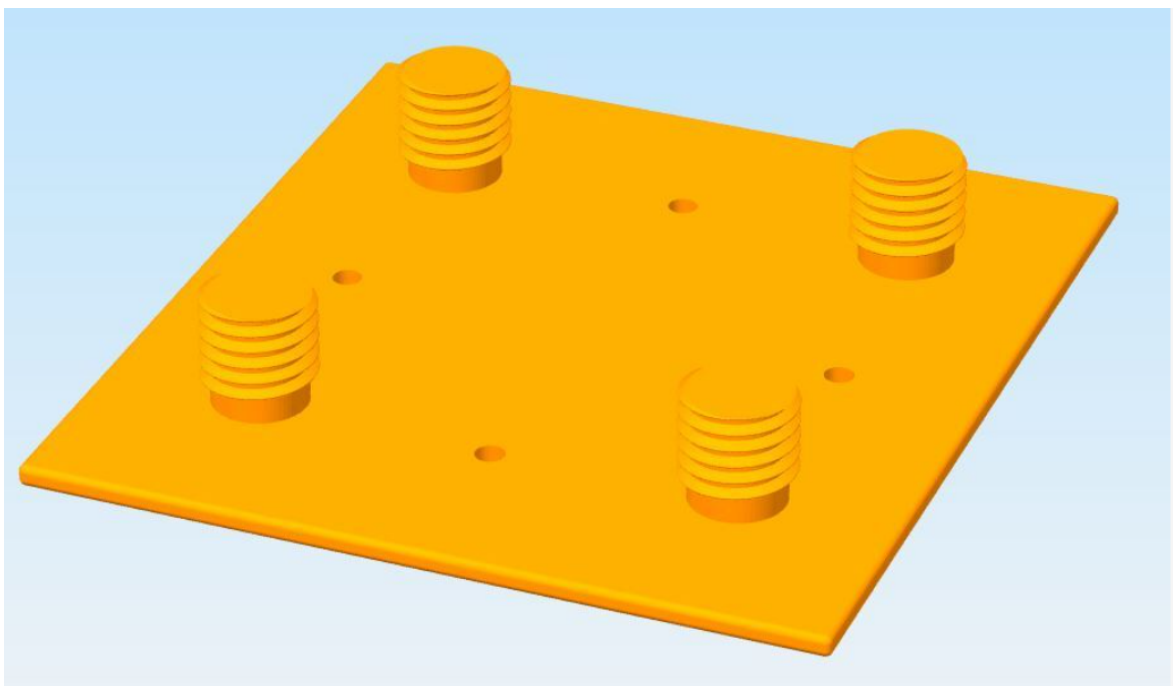




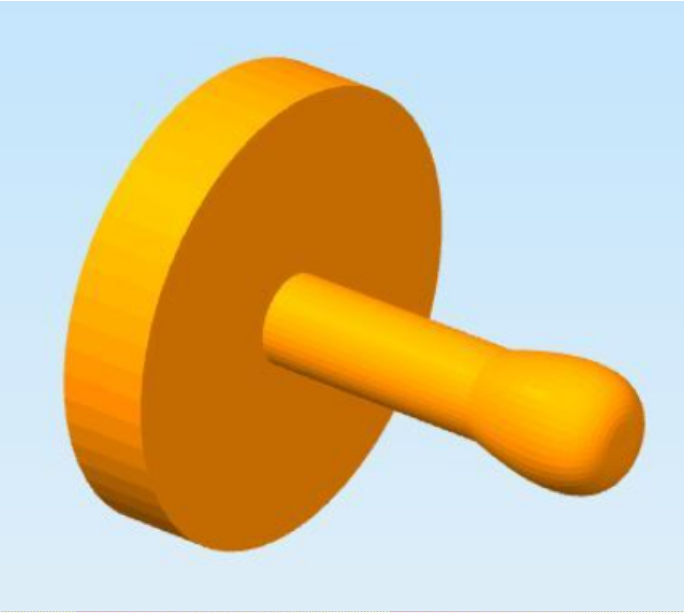
RPM_HARV_holder.JPG



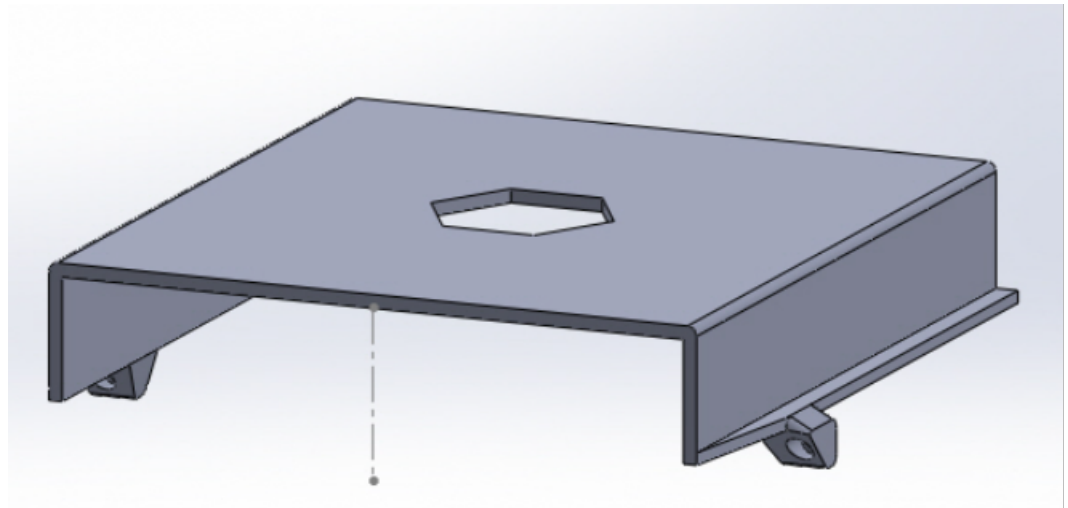
RPM_HARV_plate_single.JPG



RPM_HARV_plate_small.JPG



F Rubber Band Puller V3.JPG



F Base Centering Plate.JPG