Design and Fabrication of Payload Computer Module for the Clearpath Robotics Kingfisher M200

by

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Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

June 2014

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ABSTRACT

The Clearpath Robotics Kingfisher M200 robot is an unmanned water surface vehicle with payload autonomy capability. This allows users to develop autonomy control on an off-board computer until it is ready for use on the autonomous vehicle. The Massachusetts Institute of Technology's Battelle Autonomy Laboratory plans to utilize this feature in both teaching and research applications so that users can develop autonomous missions on off-board single-board computers and then easily integrate their missions with the vehicles when ready. Although the M200's payload bay includes a waterproof data connection port, there is no provided environmental protection for the payload computer itself. This paper documents the design and production of a waterproof payload computer module that allows for the operation of the single-board computer, data interface with the M200's on-board computer and for the attachment of additional USB components. The Raspberry Pi was selected as the most appropriate single-board computer and the Otterbox Drybox 3000 was selected as the most appropriate enclosure. Electrical circuitry was designed to allow for power to the computer, data communication with the M200 and USB connections for additional components, and combination of cable glands and panel-mounted connectors were used to allow these connections to be accessible from the outside of the enclosure while retaining a NEMA 4 waterproof enclosure rating. In order to create a robust and user-friendly module, a system of strain relief and component orientation was designed. Continuous testing and adapting of prototypes resulted in a compact, operational payload module that can easily be interfaced with the Kingfisher M200 to provide payload autonomy as well as offer two additional USB ports for the connection of additional components. This design aims to be easily reproducible by other Kingfisher M200 users, as well as adaptable to other payload autonomy applications.

Thesis supervisor: John J. Leonard
Title: Professor of Mechanical and Ocean Engineering

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1 Introduction

Clearpath Robotics' Kingfisher M200 robot is an unmanned water surface vehicle that has payload autonomy capability. This vehicle is used in the Massachusetts Institute of Technology (MIT) class 2.680: Unmanned Vehicle Autonomy, Sensing, and Communication, although it is also used by additional research projects in the MIT Battelle Autonomy Laboratory that are sharing the robotic resources. Payload autonomy allows a user to develop autonomy control on an off-board payload computer until it is ready for use on the autonomous vehicle. For example, a payload computer using autonomy software can be connected to an on-shore laptop that is used to run mission simulations. After testing and editing the mission off-board, the payload computer is connected to the autonomous vehicle so that it can physically execute the mission.

The MIT class 2.680 aims to guide students through developing and executing their own autonomous missions on the M200s. In order to allow multiple students to simultaneously work on their projects and do so without the need for the physical vehicles, they will be given payload computers to do development on until they are ready to test their work on the M200 vehicles. The vehicle's payload bay includes a waterproof data connection port. For typical failure use (splashing, possible overturning), user-supplied payloads must be environmentally sealed to an NEMA 4 rating. To this end, my thesis project addresses the design and production of a waterproof payload computer module, which includes assembling the circuitry to create the appropriate connections as well as the creation of a waterproof and accessible housing for the components.

1.1 Clearpath Kingfisher M200

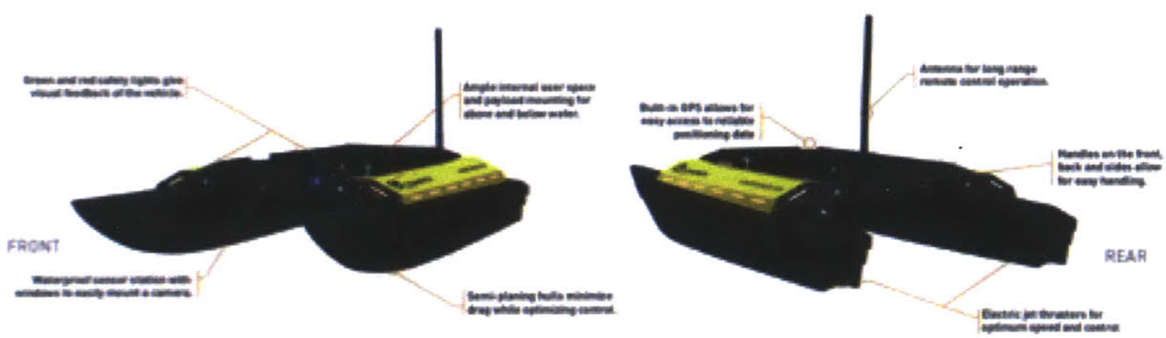


Figure 1: Clearpath Robotics Kingfisher M200 front and rear photos with annotations showing key design features

The Kingfisher M200 robot can be operated autonomously or remotely and is designed primarily for research purposes. Fully deployed, it occupies 51.2 x 37.0 x 13.4 inches and weighs 64 pounds.[1] The vehicle has an onboard computer with a 1.80GHz processor.[2] Onboard sensors include an Inertial Measurement Unit and Global Positioning System that connect to Clearpath's proprietary control system running on the onboard computer. A 9.5 x 13.4 x 3 inch payload bay includes Ethernet and RS232 serial communication ports to connect user expansion devices to the onboard computing and networking infrastructure.

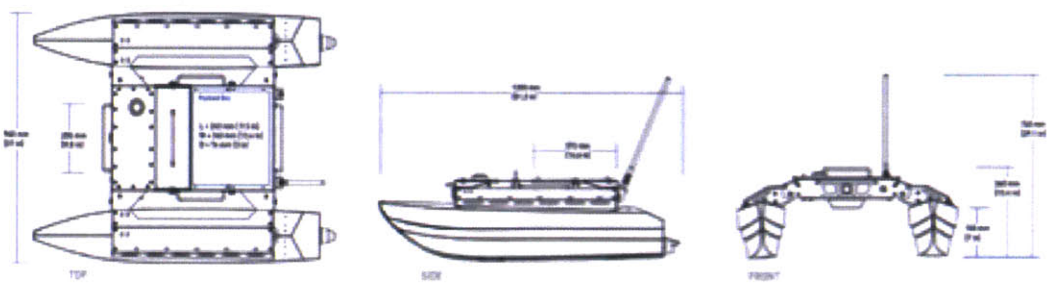


Figure 2: Clearpath Robotics Kingfisher M200 drawings showing vehicle dimensions fully deployed

1.2 The Payload Computer

Any computing device with the ability to run the GNU/Linux operating system and an onboard Ethernet port can be used as a payload computer on the M200. However, a device must be chosen for this project that is also small, affordable, offers connections for additional components and is easy for students to work with. After reviewing possible options, the Raspberry Pi Model B (Raspi) single-board computer was chosen for this project, and rejected alternatives are described below in table 1. The Raspi is powered with 5 Volts, has 2 USB ports, 512 megabytes of RAM and an Ethernet port and its operating system runs on an SD card.[3]

At 3.37 x 2.20 x 0.82 inches and 1.59 ounces, it fits easily into a waterproof enclosure that can fit into the M200's payload bay. In order to protect the board from electrical shorting to other components in the enclosure, the board is placed into its own conformal case still keeps the ports accessible. A commercially available box such as the one manufactured by Cyntech, seen in Figure 4, barely increases the unit's maximum dimensions to a volume of 3.94 x 2.75 x 1.06 inches.

[1] http://www.clearpathrobotics.com/kingfisher

[2] http://www.commell.com.tw/Product/SBC/LE-376.HTM

[3] http://www.raspberrypi.org/faqs

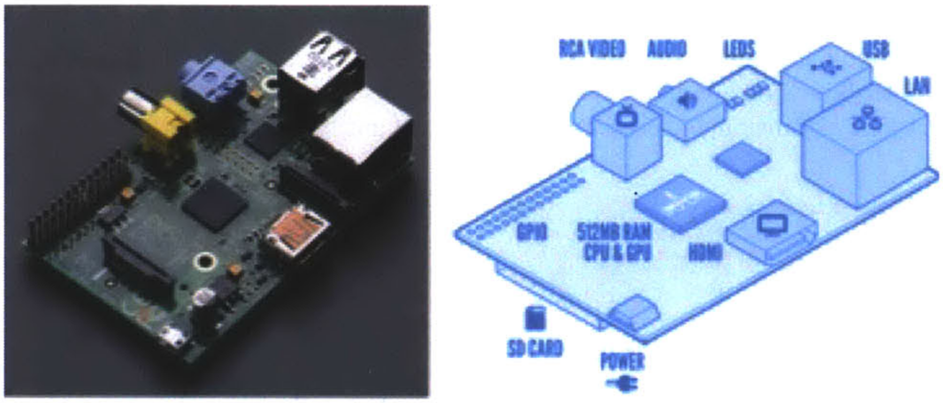


Figure 3: Raspberry Pi Model B drawing showing available connections and layout (left), and photo of physical board (right)

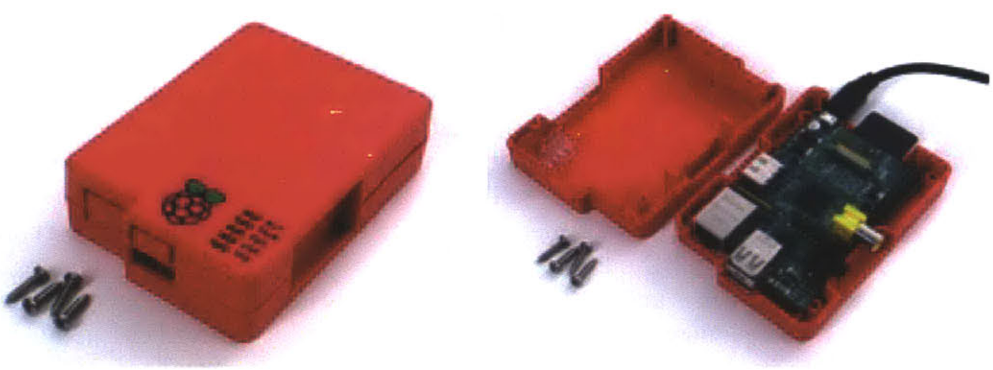


Figure 4: A Raspberry Pi case that protects the board from damage while providing access to the board's components

Rejected alternative computing units include the Gumstix and BeagleBoard but, as Table 1 shows, the Raspberry Pi is less expensive and has more USB ports than either of these alternatives. Additionally, they are smaller than the Raspberry Pi and use the same power source, meaning that a system designed for the Raspberry Pi should be easily adaptable to these smaller, similar boards. The BeagleBone Black is similar to the Raspi in many of its specifications. While the Raspi works well for the requirements of 2.680, other similar projects may want to examine the BeagleBone Black as an alternative.

Table 1: Embeddable Computer Comparison

Singler-board Computer	Cost	Power	RAM	Features	Dimensions
Raspberry Pi Model B	35.00	3.3V, 5V	512 MB	Audio, Ethernet, HDMI, RCA Video, USB x2	3.37 x 2.20 inches
Gumstix Overo EarthStorm[4]	109.00	3.5V - 5V	512MB	None	2.28 x 0.67 inches
Gumstix Tobi expansion board[5]	69.00	3.5V - 5V	N/A	Audio x 2, Ethernet, HDMI, USB	4.13 x 1.57 inches
BeagleBoard BeagleBone Black[6]	45.00	3.3V, 5V	512MB	Audio, Ethernet, HDMI, USB	3.40 x 2.10 inches

1.3 Extending the Payload Computer

A payload computer can be used not only as a method of running robotic software on the vehicle, but also as a way to integrate additional components. The Raspberry Pi has two USB ports, which can provide low-current 5V power. These allow external low-power USB-powered devices to be connected,including serial devices via USB-serial converters.

For example, the Hunter-Prey project aims to have one M200 (the "Hunter") follow another (the "Prey") around autonomously by connecting an acoustic transponder to the Prey's payload computer and having that signal received by the acoustic unit connected to the payload computer of the Hunter. This system would require the use of the onboard GPS system as well as the transponder/receiver, which the payload computer allows for. As this is just one example of the potential use of the payload computer to be designed, the module should be designed to be small to allow for other components to fit in the payload bay, as well as easily adaptable to a range of setups.

2 Design Requirements

2.1 Electrical connections

Although the Raspberry Pi has a number of available connections, such as audio and HDMI, not all of these connections are required for the purposes of 2.680 and the current research plans at the MIT Battelle Autonomy Laboratory. Instead, the required connections are power supply, Ethernet data communications to communicate with the M200's computer, and USB to connect external components.

Power Supply: The board must be powered either to its micro USB power input or its two GPIO power and ground pins. To power the Raspberry Pi while onboard the M200, a 12-volt battery supply will be mounted into the payload. Although it is possible to power the Raspi using the M200's own power supply, it is desirable to have an external battery to allow for the connection of many additional components. Therefore, a connection is needed between the 12V battery and the board's power input. Additionally, because the Raspberry Pi operates at 5V, a voltage regulator is needed to step down the input voltage.

Ethernet Data Communications: In order to allow for data communication with the M200's on-board computer, a connection must be made between the Raspberry Pi's Ethernet jack and the vehicle's Ethernet port. The M200 is fitted with a CONEC 17-10000 Ethernet connector, which mates with a CONEC 17-10001 waterproof plug.

USB: The power and Ethernet connections are enough to serve the basic purposes of 2.680 but in order to connect additional components, such as the transponders for the Hunter-Prey project, the two USB ports must also be made accessible outside of the enclosure.

2.2 Enclosure

The payload bay on the M200 is open to the air and is likely to be splashed or even accidentally submerged during use in the water. Given this environmental consideration, a minimum electrical enclosure waterproofing standard of NEMA 4 was selected as the minimum level of protection. NEMA 4 is defined as "Must exclude at least 65 Gallons Per Minute of water from 1 inch nozzle delivered from a distance not less than 10 feet for 5 minutes."[7] NEMA 4X, 6 and 6P are also acceptable as they define a higher level of waterproofing and/or corrosion resistance. This also satisfies the IEC enclosure class of IP65. The challenge is to maintain this level of environmental protection given the number of electrical connections that must pass through the enclosure. Although the computing system allows for connected peripherals, my thesis does not cover environmental protection for the peripherals except for defining which connector must be used to maintain waterproofing to the Raspi enclosure.

[7] http://www.coleparmer.com/TechLibraryArticle/511

When choosing a design for the waterproof enclosure, it is critical that all of the required components can fit where they are needed in relation to the enclosure. The inside of the enclosure requires adequate space for the Raspberry Pi board, the voltage regulator, the Ethernet and USB plugs and cables connecting all of these components. There also needs to be enough flat surface area on the enclosure lid in order to feed the four cables through and environmentally seal them.

A number of enclosure options were considered. Two commonly available waterproof enclosure brands of this scale are OtterBox and Pelican Case, which both offer a number of enclosures ranging in size and shape. An alternative option was to create a custom enclosure using laser cut acrylic held together using acrylic cement. Creating a custom case would allow for the design to be the exact size and dimensions required for this project, but would require a complex gasket arrangement to allow for a lid that can be opened, and even then could not assure environmental protection. A laptop-sized Pelican case could also be used and would undoubtedly perform extremely well in terms of waterproofing and ruggedness. However, Pelican Cases are very large in comparison to the storage space they provide due to their heavy internal padding and thick enclosure walls.[8] They are also quite expensive. The OtterBox offers a middle ground as they are less expensive and occupy a smaller footprint for the same internal volume, making this the most appropriate enclosure for this project. The 3000 model has exterior dimensions that measure at 8.813"x5.175"x2.008", with 35 cubic inches of interior space.[9]

2.3 User Considerations

Furthermore, all of these connections to the Raspberry Pi need to be removable so that users can operate the Raspi outside of the enclosure as well. Connecting the board to a regular computer for software development simply requires a USB-to-micro USB cable from the computer to the microcomputer, which provides the required 5 Volts of power and data transmission. To use the Raspberry Pi as a standalone computer, a 5V wall-plug with a micro USB end can be used to power the board, a monitor can be plugged into the HDMI port and a mouse and keyboard can be plugged into the two USB ports. Students of 2.680 will be provided with a USB-to-micro USB cable and a 5V wall-plug with micro USB end for the purposes of their project.

[8] http://www.pelican-case.com/1470.html

[9] http://www.otterbox.com/OtterBox-Drybox-3000/OTR3-3000S,default,pd.html

Figure 5: Pelican Case 1470 (left) which is large and expensive; Otterbox Drybox 3000 (right) which will be used as an enclosure for the Raspberry Pi due to its compact size and low cost

3 Components

3.1 Power Supply

The Raspberry Pi can be powered with 5V using its micro USB plug or using the GPIO pins on the board. Using the micro USB plug would require significantly more room inside the enclosure because it is located on the opposite side of the Raspberry Pi from the Ethernet and USB plugs. This means that extra room would have to be made for the relatively stiff micro USB plug on that side as well as space for the user to pull the plug in and out. A right-angled micro USB plug could alleviate this issue, but readily available micro USB plugs bend the wrong direction for this purpose. An appropriate right-angled micro USB plug could be made by removing the strain relief from the plug and using epoxy to fix the cable bent into a right angle but this would run the risk of fatiguing over time and would still not completely remove the issue, as it would still be a tight fit inside the enclosure.

A suitable alternative is to power the microprocessor using its GPIO pins,. A female-female cable can be plugged into the 5V and GND pins (pins 4 and 6 respectively, as seen in Figure 5[10]) with the other end of the cable sticking out of the side of the case.

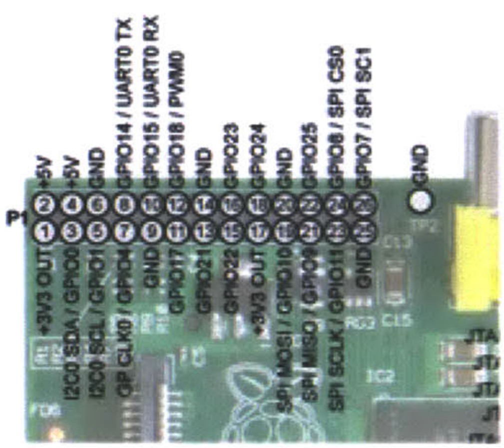


Figure 6: GPIO pin layout on the Raspberry Pi Model B board. The board will be powered by connecting the 5V input to pin 4 and the Ground wire to pin 6.

Using a cable terminated with a hobby-servo type connector to create these connections means that the cable protruding from the board is very thin and flexible and so can be oriented in the most convenient position. Providing each Raspi unit with a servo cable plugged into its GPIO pins is inexpensive and still allows the user to power the Raspberry Pi using the micro USB plug when used outside of the enclosure. The protruding end of

[10]http://www.raspberry-projects.com/pi/pi-hardware/model-b-io-pins

the cable is a female connector in order to prevent accidental shorting when 5V comes to the pins when the Raspi is powered through the micro USB.

The Raspberry Pi operates at 5V and putting a higher voltage through the board will damage it. Therefore, a voltage regulator is needed inside the enclosure between the 12V battery source and the board. Using a buck converter instead of a linear regulator is desirable because they have much higher efficiencies and dissipate less heat, which could be dangerous in the tightly sealed enclosure. A Universal Battery Elimination Circuit[11] fits the needs of this project - it is small, affordable and can convert an input voltage of up to 23 volts down to 5 volts - and is commonly used in hobby and electronics projects which have similar needs. These regulators, as seen in Figure 6, also conveniently have a servo cable with a "JR style"[12] connector at the end, which mates with the cable provided that protrudes from the Raspberry Pi case.

Figure 7: A universal battery elimination circuit. The bare wires take an input voltage between 5 and 23 volts, and the circuit outputs 5V at 3A.

In order to input 12V to the regulator, a cable must be connected from the terminals of the battery, into the enclosure and to the voltage regulator. A waterproof power pigtail cable, as seen in Figure 7[13], can be used, with the male end attached to the battery and the female plug affixed to the enclosure.

The female end is mounted through the box and will have the voltage regulator connected inside the enclosure. In order to keep the voltage regulator removable in case of damage, the pigtail wires will be fitted with a female plug and the input wires of the regulator with a corresponding male plug. The configuration ensures that if the battery was

[11] http://www.adafruit.com/products/1385

[12] https://www.servocity.com/html/connector_types.html

[13] http://www.adafruit.com/products/743

Figure 8: Waterproof power pigtail cable. The female plug is mounted on the box and the male plug attached to the 12V battery.

connected but the regulator was not plugged in, there would not be any live wires that could short to each other, causing damage to the battery. The male pigtail cable easily plugs in and the threaded ring creates a waterproof connection by tightening over the O-ring on the male plug. The end of the male cable will be fitted with battery connectors, as seen in Figure 8.

Figure 9: Battery connectors are attached to end of power pigtail cable. These connectors fit over the battery terminals to power the payload computer module.

With this circuitry, the Raspberry Pi will be properly powered but requires the power pigtail cable to pass through a hole in the enclosure, meaning the enclosure is no longer waterproof. Trying to seal the hole around the cable using caulk or epoxy may not remain waterproof for the life of the payload module. A cable gland, as shown in Figure 9[14], is used

[14] http://www.adafruit.com/products/762

to solve this problem. A gland is installed around a cable and is tightened over the cable in order to create a waterproof seal. The gland is then mounted in a hole in the enclosure and uses an O-ring seal to waterproof the mounting hole. This allows cables to effectively pass through the enclosure wall without compromising the waterproof functionality.

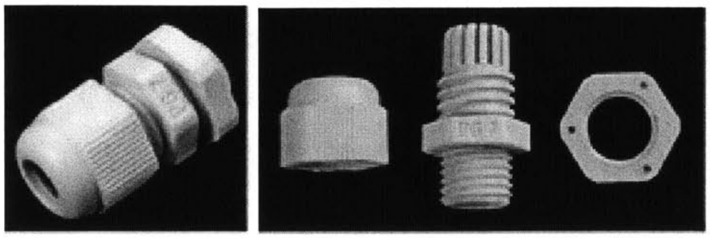


Figure 10: PG-7 cable gland used to waterproof cables, fully assembled (left) and disassembled (right)

The power pigtail cable used in this design has a cable diameter of 0.18 inches which fits into a PG-7 cable gland. However, in order to create the closest fit over the cable and therefore increase the waterproof performance of the gland, the cable diameter can be increased using heat wrap on the cable. Additionally, the gasket inside the gland can be replaced by surgical tubing with a similar outer diameter but smaller internal diameter. Depending on the cable being used, a combination of these techniques can be used to create the tightest fit between the cable and gasket, and between the gasket and gland. Additional waterproofing can be given to the mounting hole by putting an O-ring around the gland such that it is compressed between the inside of the enclosure and the tightening nut. Using a PG-7 gland for the power supply cable will occupy approximately a 0.677"diameter on the surface of the enclosure and require a 0.452" diameter mounting hole.

3.2 Ethernet Data Communications

A Category 6 (Cat 6) Ethernet cable is required for connection to the M200, with one end plugged into the Raspberry Pi and the other to the M200 Ethernet port. The Cat 6 cable used for this project has a diameter of 0.24 inches and also fits into a PG-7 gland. Cable diameters can vary between different cables and so the previously stated methods of adding heat shrink or replacing the gland gasket can be used to create a tight fit around the cable. It is also desirable to use a cable that is smooth and somewhat compressible to create the tightest seal.

Additionally, the connection between the M200 Ethernet port and the Ethernet cable from the Raspberry Pi must be waterproof. The Kingfisher M200 Ethernet connector is a

CONEC 17-10000, which mates with a CONEC 17-10001, as seen in Figure 10.[15]

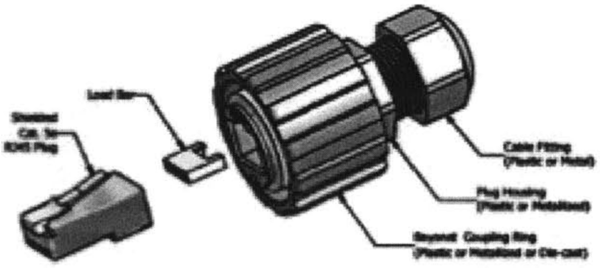


Figure 11: Ethernet connector system components. The load bar and shield are attached to a CAT 6 cable which is fed through the connector housing.

Because the cable just fits through the gland without much clearance, it is not possible to install an Ethernet cable with plugs on both ends, as both ends will exceed the gland opening sizes. Instead, one end of the Cat 6 Ethernet cable is cut off in order to insert it into the Connector System and the gland. Once inserted, the shielded RJ45 plug can be crimped onto the cut end to recreate the original cable. After this, the cable cannot be removed from the gland or Connector System without cutting the plug off again.

3.3 USB

Instead of requiring a cable to pass through the enclosure wall, the enclosure requires plugs on its exterior so that any USB device can be plugged into it. A panel-mounted connector is a waterproof connector plug with a wire pigtail on the other side. This connector is mounted in a hole in the enclosure and tightened down over an O-ring to waterproof the hole. Installing panel-mounted USB plugs on the outside of the enclosure with a USB plug on the USB wire pigtail inside the enclosure will essentially bring the Raspberry Pi USB plugs to the outside of the enclosure. However, panel-mounted connectors would occupy a large area on the enclosure. A more efficient use of the available space is to use mini USB connectors, which are smaller, and use a USB to mini USB converter on any USB devices to be plugged into the payload module. Figure 11 shows a mini USB connector that has a maximum diameter of 0.974", which is small enough to fit two of them on the enclosure.[16] Therefore, in order to connect external components to the payload module via USB, they will need to adapt their connectors to plug into the mini USB connector.

The pigtail from the mini USB connector needs to be attached to a USB plug inside the enclosure so that it can be plugged into the microprocessor. One option is to purchase

[15]http://www.mouser.com/new/conec/conec-rj45-ip67/

[16]http://www.mouser.com/ds/2/57/Buccaneer-2010_MiniUSB-10795.pdf

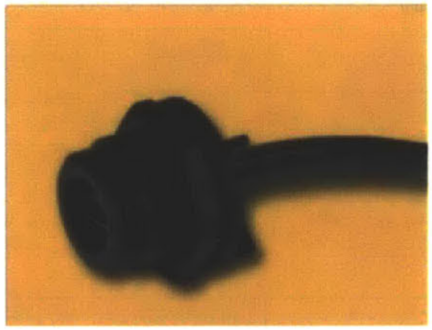


Figure 12: Photo of panel mounted mini USB connector which is mounted to the outside surface of the enclosure with the cable pigtail inside the enclosure

a USB plug kit and solder the mini USB pigtail wires to the plug. However, the casing on this plug does not provide great strain relief and may quickly fatigue. Additionally, the pigtail cable is fairly thick which makes it inflexible and hard to orient properly inside the enclosure. Instead, the last 2 or 3 inches of a USB cable was cut from another USB device (such as a computer mouse) and soldered to a cable pigtail that was cut down to approximately 1 inch - just enough to allow for enough wire length to create a quality solder joint. This technique places the weakest point of the cable (the solder joints) further away from the point that will undergo the most use, as well as allow for a thinner and more flexible cable to be used. Due to the limited amount of space in the enclosure, the Raspberry Pi has a fairly fixed position and so the USB plugs should be the exact length to plug in when the microprocessor is inserted in the box. However, if the cables are too long, they can be wrapped around themselves to reduce their length.

Since these connectors will not always be needed since the system does not rely on external USB devices, screw-on caps can be used to seal the connectors outside the box. It is recommended that even when not in use, the USB plugs be plugged into the Raspberry Pi as they help to orient it and would take up extra space if not plugged in.

With these four connections (power supply, Ethernet and 2 USB), users will be able to power the microprocessor, transmit data between the microprocessor and the vehicle via Ethernet, and connect additional components via USB. The entire layout of required components to achieve this is shown in Figure 12.

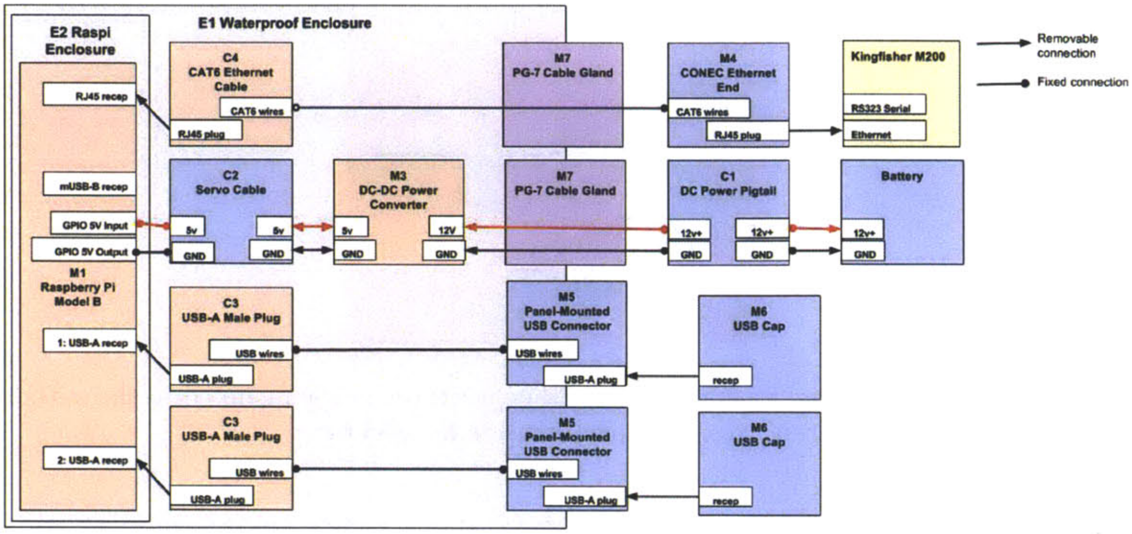


Figure 13: The required components for the waterproof payload computer module, as well as the electrical connection layout to make the power, Ethernet and two USB ports accessible

4 Enclosure Design

The OtterBox 3000 has a 2.705" x 6.7" flat area on the top and bottom of the box that can be used to mount the 2 glands and 2 panel-mounted connectors onto. Due to the shallowness of the enclosure, these cannot be placed directly above the Raspberry Pi. This leaves a 2.26" length of the workable area to mount the four cable connectors. Because of the limited space inside the enclosure and to prevent closing the lid on wires, it is desirable to minimize the length of cable that must be stored inside. This is in contrast to providing service loops for the convenience of attaching connectors during Raspi installation and removal. By orienting the Raspberry Pi at one end of the box with the SD card at the edge of the box and the four cables at the other end close to the Ethernet and USB ports, the required cable length is minimized.

However, routing the cables directly from these holes to their plugs would require the cables to be bent at sharp angles to reach the plugs inside the box. This can lead to wire fatigue resulting in broken connections at solder joints over time. Adding strain relief to the cables to reduce flexing at connectors and weak points mitigates this problem and contributes to a shorter cable length by forcing connector orientation toward the destination ports on the Raspi. Because the USB cables are created by soldering a USB plug cable to the pigtail from the connector, this solder joint will be the weakest point of the USB cable. Affixing the cable to the box after the solder joint will isolate any force on the cable from this weak point. Strain relief is needed on the power cable to protect the attachment points of the voltage regulator, so strain relief should be placed on the output wires of the regulator to isolate the force from the user. The Ethernet cable does not have a notably weak point other than the plug itself and so the strain relief acts primarily to keep the cable in the optimal orientation.

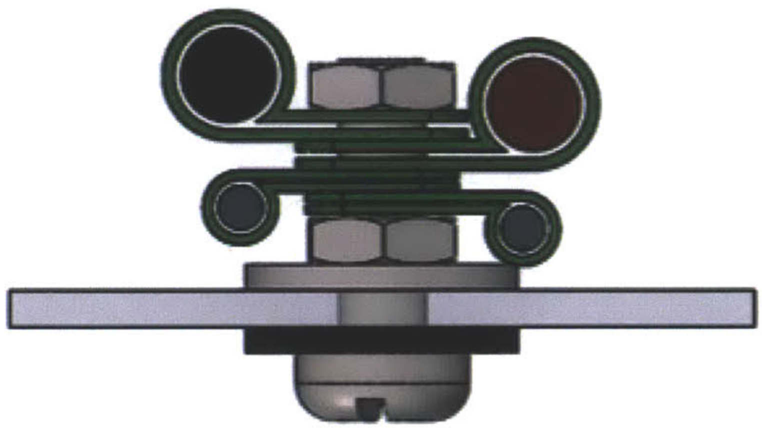
In order to minimize the space used to provide strain relief to the cables, I designed a novel stacking approach. Four plastic loop clamps (similar to Figure 14[17]) are stacked along a single pole, aligned about a screw that is mounted into the enclosure. The hole that the screw is mounted through is waterproof by putting a rubber gasket between the screw head and the enclosure outer surface, and compressing the gasket by tightening a nut on the inside surface of the enclosure. Then the fasteners are stacked with the USB cables on the bottom and the power and Ethernet cables above. Another nut at the top tightens the four cable fasteners into place, as shown in Figure 15.

Figure 14: Diagram showing how strain relief for the cables is implemented on the inside of the enclosure using cable fasteners stacked on a screw

Due to the limited amount of space and the relatively large bending radii of the cables, the two cables mounted closest to the Raspberry Pi will have to be oriented facing away from the microcomputer and then looped back around to plug into the board. Since the USB plugs will not always be used, it is desirable to minimize the USB cable lengths so that they are not in the way when not plugged in. Placing them furthest from the Raspberry Pi means that the cables do not need to be looped and so less cable length is needed. Figure 16 shows the chosen configuration of the connectors and cables based on the stated design considerations.

The Raspi does not require any explicit mount to the enclosure. The stiffness of the cable plugs and the limited amount of space in the enclosure means that the Raspberry Pi do not shift around much once placed into the enclosure. Empirical testing demonstrates

[17]http://www.grainger.com/product/DOLPHIN-COMPONENTS-CORP-Cable-Clamp-14X933



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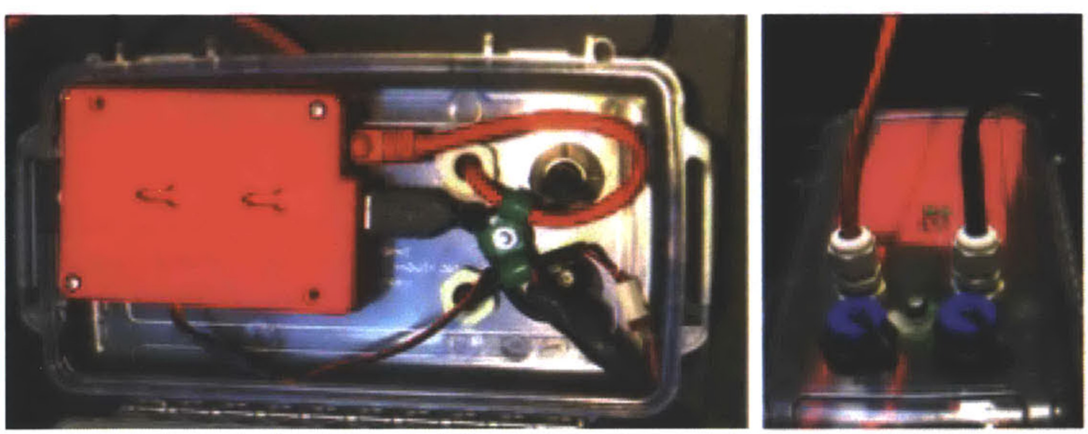

Figure 16: Photo of connector and cable configuration inside (left) and outside (right) enclosure that minimizes required space and cable length

that small amount of movement are not problematic, even with vigorous shaking of the enclosure.

Manufacturing the five holes in the enclosure - two for the cable glands, two for the panel-mounted connectors and one for the strain relief bolt - presents a challenge as the OtterBox is made of polycarbonate, which can either melt or crack under pressure from a mill or drill press. Additionally, the panel-mounted connectors are keyed in order to prevent rotation and creating a circular hole would not mate with this feature. In fact, using any machine tool is challenging, as the OtterBox does not lend itself well to being held in a clamp, which would be required for safe machining practices. After testing on a spare OtterBox, it was determined that it is possible to create holes through the polycarbonate using a laser cutter. In order to protect nearby areas of the box from charring, both sides of the box were lined with painter's tape. This method produced accurate, repeatable and aesthetic results, which allowed for all of the components to easily be assembled on the enclosure. In addition, laser-cutting allowed for keying, which would not have otherwise been possible.

Once I manufactured a prototype payload module and all electrical connections were made and tested, I tested the waterproofing ability of the module by removing the Raspberry Pi from the enclosure (so that in case of a leak, the board isn't damaged), fully closing the OtterBox and submerging it in water for approximately one minute. Then, I removed the box from the water and opened it to check that there was no dampness inside the enclosure. The first test resulted in traces of water leaking in the PG-7 gland holes, but inserting an O-ring around the threads of the gland between the inside of the enclosure and the gland nut solved this issue. In some cases, water entered the enclosure from around the Ethernet cable. Depending on the Ethernet cable used, a combination of replacing the gasket with surgical tubing and increasing the cable diameter with heat shrink tubing solved this. As Ethernet cables range in diameter and compliance, I would recommend testing a range of waterproofing solutions for the cable. Once all updates were made, the Raspberry Pi was put back into the enclosure so that the payload module can be installed onto the Kingfisher M200 for use.

Figure 17: Fully assembled payload module installed in the Kingfisher M200's payload bay

5 Conclusion

Based on the design requirements of the MIT class 2.680 and the MIT Battelle Autonomy Laboratory, a payload computer module was designed for the Clearpath Kingfisher M200 surface vehicle. The necessary electrical components, waterproofing methods and component configuration were determined in order to make the payload module most cost- and space-efficient, as well as simple to manufacture, operate and maintain. For the purposes of this project, the Raspberry Pi microprocessor was enclosed in a waterproof OtterBox, with its power, Ethernet and two USB ports made accessible outside the enclosure. It was found that using commercially available parts provided the best waterproofing methods without significantly increasing the cost of producing the enclosure, and produced a compact module that leaves plenty of room in the payload bay of the M200 for the power source and additional components.

In designing and building the payload module, the largest unexpected issue to surface was the leaking of the PG-7 cable glands. Although the glands were rated at PG-7 level waterproofing, they did not completely seal the cables from the water. Instead, I replaced some of the gland gaskets with surgical tubing and placed an additional O-ring between the nut and the enclosure surface. Anyone attempting to reproduce the work specified in this paper may want to try a different PG-7 cable gland or else they will have to alter the glands to better fit the cables and mounting holes.

This enclosure could be redesigned to make use of the other connections that the Raspberry Pi offers, such as the HDMI port, the audio jack or the additional GPIO pins. It is possible by replacing the USB connectors, or by using a larger enclosure that would fit more than four connectors. This may be particularly relevant if an alternative to the Raspberry

Pi is used, as this may change the types of available connectors and their orientation. The component and wire configuration used in this project may not be optimal for a different embeddable computer with plugs in different locations, although they will all require power and data communication to the M200.

Futhermore, the characteristics of this payload module can be adapted for use in applications other than on the Kingfisher M200. Many autonomous vehicles can be controlled using devices such as the Raspberry Pi and require environmental protection. Even with its current design, the payload module could be used to control any autonomous vehicle that communicates via Ethernet and uses autonomous software that operates on a GNU/Linux system. Changes to the module could be made to better suit the needs of another autonomous system, such as by changing the connector types or communication medium. In all cases, it is critical that all openings in the enclosure are completely sealed, that strain relief isolates the forces on the cables from their weakest points, and that there is no risk of having live bare wires which could short-circuit. Additionally, compactness, affordability and neatness are desirable qualities in order to allow for more use of the vehicle's payload area and for easy assembly and debugging.

A Bill of Materials

Table 2: Materials used to produce the waterproof payload computer module

Type	ID	Description	Unit Cost	Quantity	Total Cost
Enclosure	E1	Otterbox Drybox 3000	20.00	1	20.00
Enclosure	E2	Raspberry Pi Case	12.50	1	12.50
Module	M1	Raspberry Pi Model B	35.00	1	35.00
Module	M2	4GB SD Card	9.95	1	9.95
Module	M3	DC-DC Power Converter	9.95	1	9.95
Module	M4	CONEC Ethernet end	7.08	1	7.08
Module	M5	Panel-mounted USB connector	10.79	2	21.58
Module	M6	USB cap	2.24	2	4.48
Module	M7	PG-7 Gland	1.95	2	3.90
Module	M8	PG-7/9	Internally sourced	1	0.00
Cable	C1	DC Power cable	2.50	1	2.50
Cable	C2	Servo cable	Internally sourced	1	0.00
Cable	C3	USB cable plug	Internally sourced	2	0.00
Cable	C4	CAT 6 Ethernet cable	Internally sourced	1	0.00
Misc	N/A	Screw	Internally sourced	1	0.00
Misc	N/A	Washer	Internally sourced	1	0.00
Misc	N/A	Nut	Internally sourced	2	0.00
Misc	N/A	O-ring	Internally sourced	2	0.00
Misc	N/A	Rubber gasket	Internally sourced	1	0.00
Misc	N/A	Male plug	Internally sourced	1	0.00
Misc	N/A	Female plug	Internally sourced	1	0.00
Misc	N/A	Battery terminal plug	Internally sourced	2	0.00
Misc	N/A	Cable fastener	Internally sourced	4	0.00
Misc	N/A	Heat shrink tubing	Internally sourced	N/A	0.00
				Total	**126.94**

Table 3: Online purchase locations for parts purchased for waterproof payload computer module

Type	ID	Description	Retailer	Product Number
Enclosure	E1	Otterbox Drybox 3000	www.adafruit.com	339
Enclosure	E2	Raspberry Pi Case	www.adafruit.com	1067
Module	M1	Raspberry Pi Model B	www.adafruit.com	998
Module	M2	4GB SD Card	www.adafruit.com	1537
Module	M3	DC-DC Power Converter	www.adafruit.com	1385
Module	M4	CONEC Ethernet end	www.mouser.com	631-17-10001
Module	M5	Panel-mounted USB connector	www.mouser.com	167-PX0457
Module	M6	USB cap	www.mouser.com	157-PX0484
Module	M7	PG-7 Gland	www.adafruit.com	762
Cable	C1	DC Power cable	www.adafruit.com	743