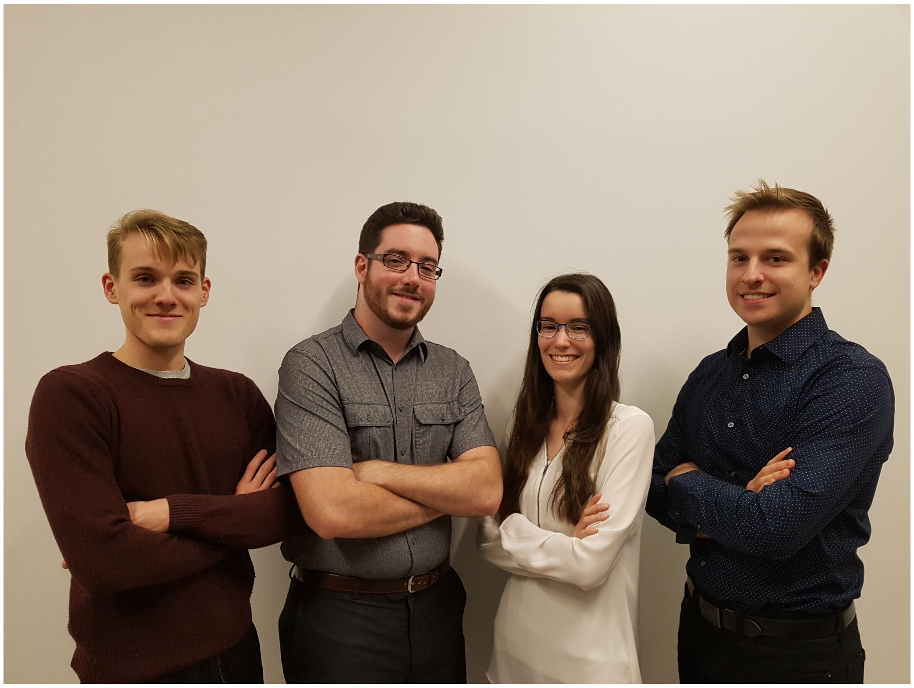
Waterfront 2A - Literature Report
MCG4322



Waterfront Robot 2A
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1 Project Charter

1.1 Mandate

The goal consists in creating a rugged device which uses a biomimetic locomotion system to remove waste from waterfronts. It must be self-reliant and be resistant to exterior environments such as areas with minimal accessibility, weather and rough terrain.

1.2 Scope

The team is composed of two separate groups which work together to design a solution. One group (B) is in charge of the garbage collection system, garbage holding tank and associated detection sensors. The other group (A), which is the subject of this report, is responsible for the design of the biomimetic locomotion system, the chassis, the solar power system, the integration of associated electronic controllers and consideration for the integration of the litter removal system.

The device must operate under harsh environments including cold and hot temperatures, rain, salt, water, wind, humidity, mud, rocks and sand. The device's locomotion is also required to operate in arduous topography and low accessibility terrain found near shore lines. This includes sand, pebble beaches, slippery surfaces and obstacles such as rocks, plants, prickly shrubs, grass, uneven landscape and shallow water. No continuously rotating joints, such as wheels, can be used for locomotion.

The device's power systems must be self-powered using solar energy. It must require no human intervention, other than for emptying the collected garbage. It should also be resistant to vandalism.

2 Literature Review

2.1 Standards, codes and rules

Based on the research completed and the number of results found regarding standards, codes and regulations; laws, regulations and standards applicable to autonomous robots, due to their relatively recent introduction to the market, have yet to be published. Some of the existing standards can still be used as a baseline for the design of new autonomous robotic systems.

Table A.1 found in the appendices contains ISO, ASTM, RIA and IEC standards and regulations for manufacturing equipment, service robots and heavy machinery, which could apply to the design, manufacturing, and use of autonomous robots in public environments. These standards and regulations include test methods to determine the mobility of the robot, design criteria for public and worker's safety, and regulations regarding the manufacturing, use and consumption of products in Canada. As stated by ISO: "It [the standard] does not apply to non-industrial robots, although the safety principles presented can be useful to other areas of robotics" [1].

2.2 Biological Locomotion

Locomotion is the combination of movement resulting in a progression from one location to another. Animal locomotion has evolved through natural selection to enable feeding, reproductive, anti-predator and habitat building behaviours. [2]

Locomotion must first be separated into two main categories: active and passive Locomotion. Passive locomotion is dependent on the environment. Typical animals showing this behaviours include jelly fish, spiders, insects, crustaceans and parasites. Wind, currents, tide and other natural energy are the main source of energy for passive locomotion. [2]

Active locomotion enables animals to purposely progress from one location to another. Active locomotion can be separated into the five mediums found on earth: marine, fossorial, terrestrial, aboreal and aerial. [2]

As the robot must use biomimetic locomotion, the following is a rapid review of limbs used by terrestrial animals. Figure 1 illustrate a homologous limb morphology comparison and Figure 2 depicts the main differences in limbs used by insect and crustacean.

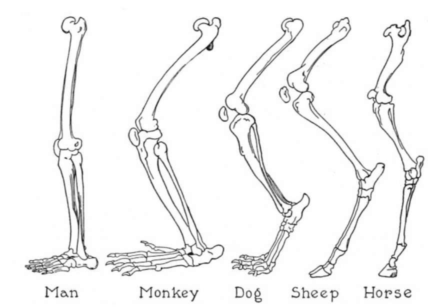

Figure 1: Comparative Homologous Structure [3]

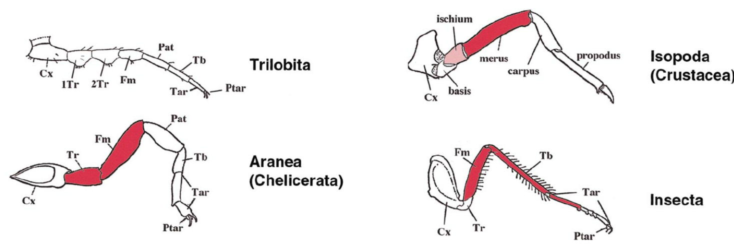

Figure 2: Insect and Crustacean Limb Comparison [4]

2.3 Existing Solutions

In 1878, Leland Stanford, then Governor of California, commissioned Eadweard Myrbridge to find out whether, when trotting, all four of a horses feet left the ground at the same time [5]. It was proven to be so, and for almost a century, various mechanical designs with fixed moving patterns emerged. In the 70s, digital computers allowed for on-the-fly kinematic calculations, resulting in more sophisticated mechanical designs and control methods. In 1984, Dr. Marc Raibert developed a hopping robot with a custom control system, and in 1986 released his seminal piece *Legged Robots that Balance*, covering control methods for robots that are monopedal, bipedal, quadrupedal and beyond. Since then, the biomimetics scene has exploded, with Dr. Raibert founding Boston Dynamics, arguable the best known company creating the class of robots. This section of the literature report will detail various existing biomimetic robots from the last decade.

2.3.1 MiniHyQ

MiniHyQ is a quadrupedal, hydraulically actuated robot developed by Hamza Khan (see Figure 3) [6]. It builds upon the work of various other quadrupedal, hydraulically actuated robots such as Boston Dynamics' Wildcat, Spot and BigDog, MIT Cheetah, and StarI-ETH, among others. It was, at the time of publication, the lightest hydraulically actuated quadrupedal robot, weighing 35kg with the on-board hydraulic power pack, in contrast to the similarly sized, 120 kg BigDog [7]. Its hydraulic system has a maximum power consumption of 5.5 kW.

MiniHyQ has four 3 DOF hydraulically actuated legs; the hip adduction-abduction and knee flexion-extension are powered by Fluitronics AZ013 linear hydraulic actuators, while the hip flexion-extension is powered by an unnamed single-vane rotary hydraulic actuator [7]. Thanks to a unique 4-bar linkage design, the isometric knee has a changeable center of rotation much like the human knee, providing 180° of rotation, an improvement on the 120° range of motion found on the original HyQ and BigDog that limited their mobility and ability to self-right after an incident. It also improves the torque profile, resulting in a smoother motion.

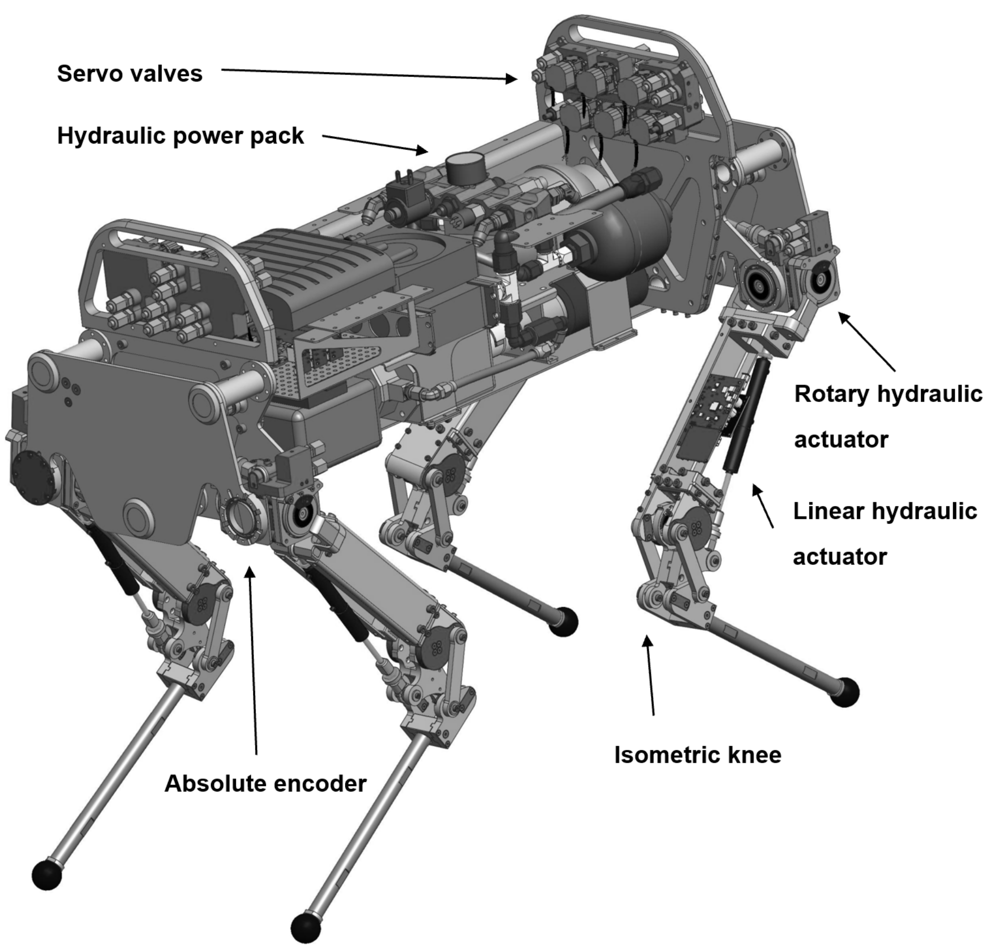

Figure 3: CAD model of MiniHyQ [7]

2.3.2 GOAT

GOAT is an omni-directional leg morphology designed by Simon Kalouche. It is shown in Figure 4. It provides a more consistent force profile across the entire leg work-space than traditional series-articulated or redundantly-articulated morphologies. It also provides excellent energy delivery, low limb inertia and high limb acceleration [8]. Each leg's mass budget (ratio of actuator mass to total mass) is 58%, compared to 40% and 24% for Penn Minotaur and MIT Cheetah.

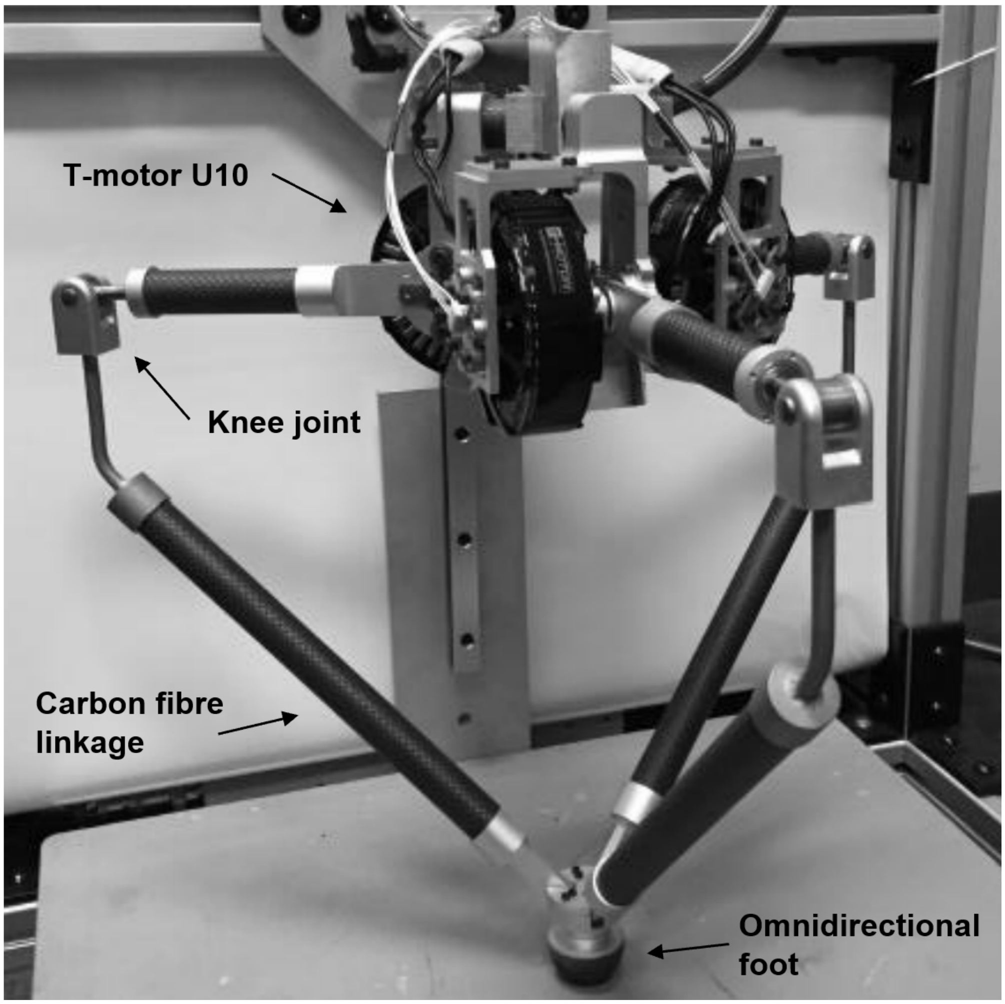

Figure 4: GOAT omni-directional leg [8]

2.3.3 Stanford Doggo

The Stanford Doggo, as shown in Figure 5, is a small quadrupedal robot created by the Stanford Student Robotics team [9]. It is designed to be low cost, lightweight and agile. Its overall price is estimated at around $3000 and the robot weighs only 4.8 kg. Its leg morphology is made to mimic some of the animals which have the best vertical jumping agility, such as the galago. This is done using a SCARA flavored linkage mechanism with two degrees of freedom (each leg can rotate 360° and change its height by compression/extension). This allows the Doggo to perform walking, trotting, bounding and pronking. To power the Doggo, two batteries are used which together can provide 44.4 Wh of energy. The maximum continuous power consumption is 840 W [10]. The controller system consists of one micro-controller that calculates leg trajectories and sends commands to four ODrive motor controllers (one for each leg). Power is distributed from the battery to the various electric components via a power distribution board [10].

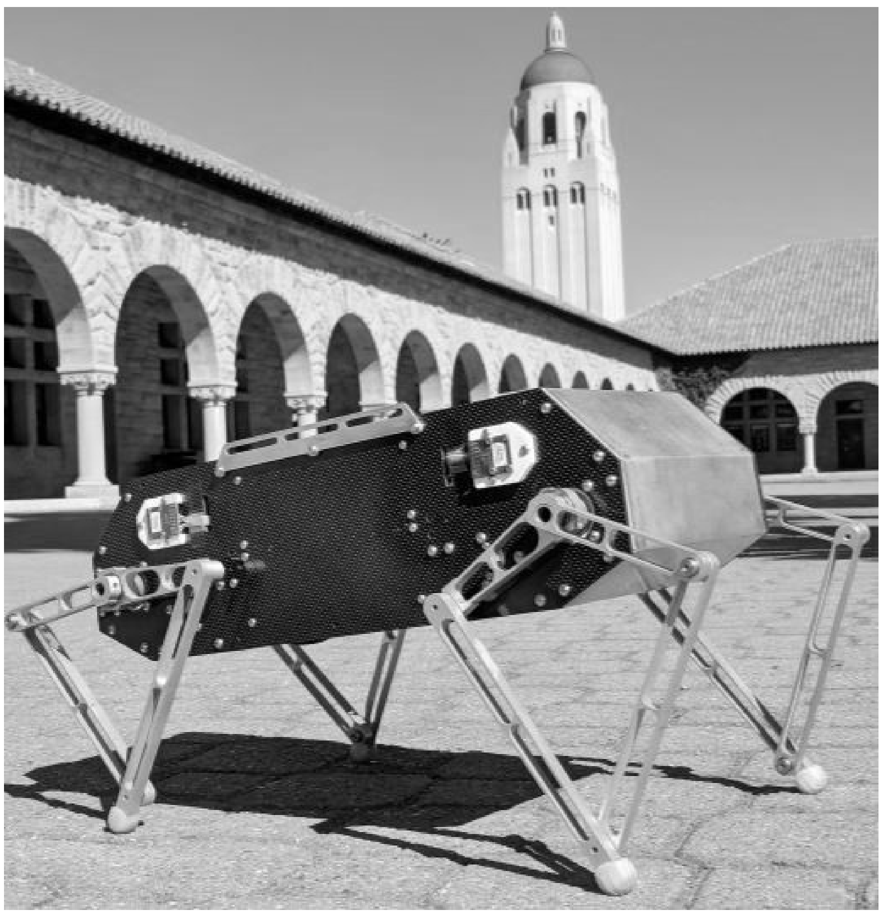

Figure 5: Stanford Doggo quadrupedal robot [10]

2.3.4 Machining Hexapod

Murschiduzzaman et al developed a small hexapod robot, shown in Figure 6 [11], to act as a portable CNC machine, reducing the need for large, permanent equipment [11]. Its six-legged design provides additional mechanical stability, compared to the previous quadrupedal robots which rely more heavily on state-of-the-art controls to maintain their stability [12]. System weight and power were not provided by the author.

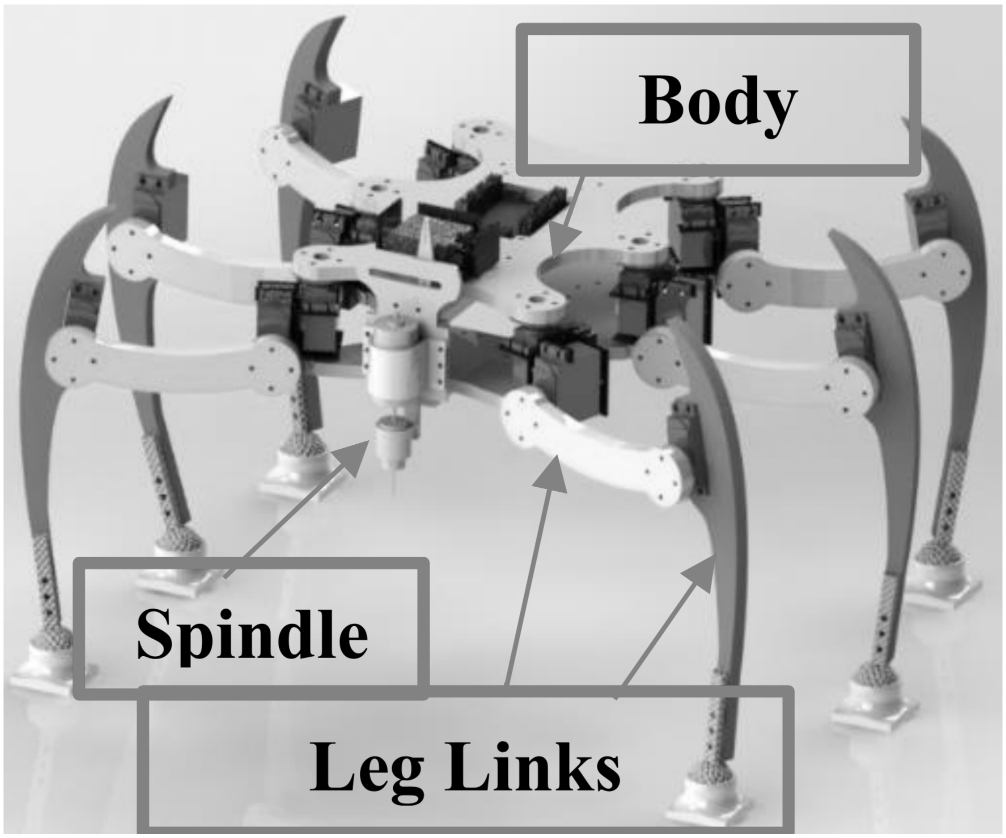

Figure 6: Hexapod robot; note the spindle attached for CNC-ing small parts [11]

2.3.5 Hexapod v2.1

Hexapod v2.1 is a small hexapod robot designed and built as a personal hobby project by an internet user named Smallp Tsai [13]. The hexapod illustrated in Figure 7 consists of six 3D printed legs and a chassis. It uses the tripod gait which provides constant stability on rough terrains. Each leg is driven by three MG92B servo motors that are controlled by a set of PCBs and powered by a 7.4 V battery. Each servo motor can produce a stall torque of 3.5 kg/cm and an operating speed of $\frac{60^\circ}{0.08\ \mathtt{sec}}$ when powered with 6 V [14]. It is capable of moving forward in a linear or curvilinear motion. The hexapod has also a climb mode which slightly elevates its body and increases the vertical displacement of each leg when going up a slope.

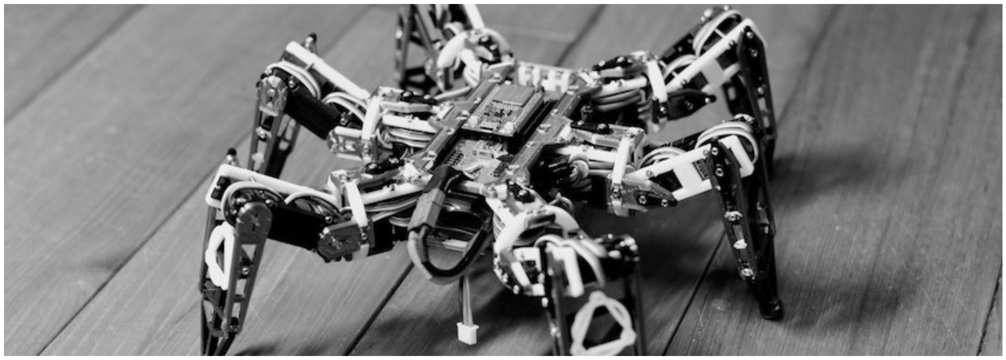

Figure 7: Hexapod v2.1 [13]

2.3.6 CRABSTER200

CRABSTER200 (CR200) is a large hexapod robot designed by the Korean Institute of Ocean Science and Technology (KIOST) [15]. Its main purpose is to conduct seabed mapping and other surveying activities on the seabed at a depth of approximately 200 m. Each joint of the 4 DOF legs includes a motor, giving a subtotal of 24 motors dedicated to the locomotion of the hexapod. Nitrile rubber type O-rings and dual O-rings are used to offer a watertight housing for each joint. CR200 is also equipped with a gripper in each of its front legs, and houses other devices in its hull such as cameras, sensors, and communicating equipment, as shown in Figure 8.

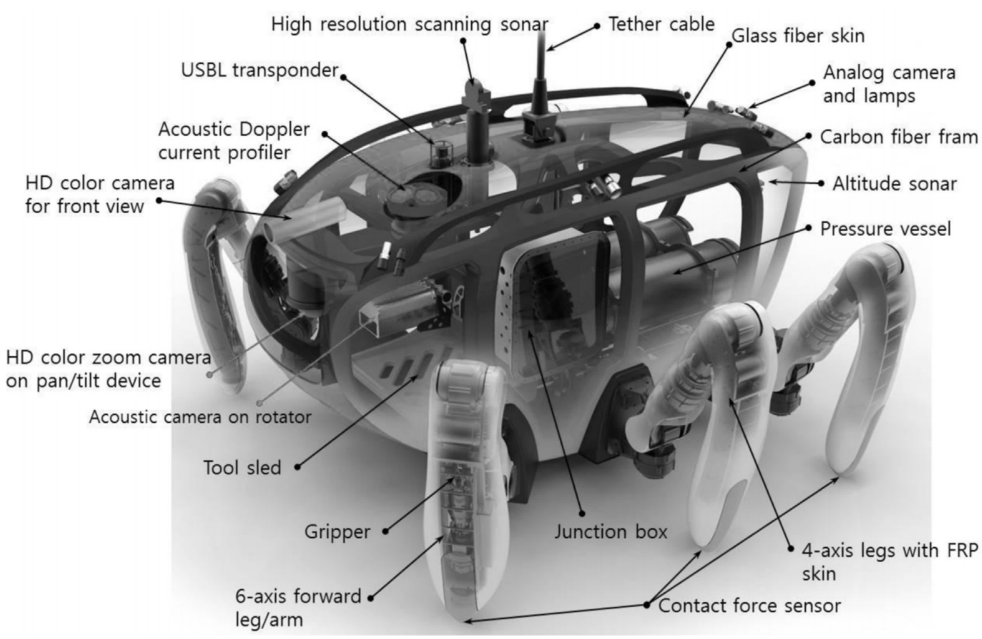

Figure 8: Concept of multi-legged seabed walking robot (CR200) [15]

2.4 Relevant Sub-systems

2.4.1 Locomotion

Locomotion for ground-based biomimetic robots is usually achieved using a set of animal-like legs. The following section presents the leg morphologies of various robots in greater detail.

2.4.1.1 MiniHyQ

MiniHyQ uses a series-articulated leg morphology [7]. The upper leg is composed of a folded 1.5mm aluminium sheet while the rest of the leg linkages is milled aluminium parts [6]. Absolute encoders and torque sensors shown in Figure 10 assist in determining leg position and acceleration. Figure 9 demonstrates the design.

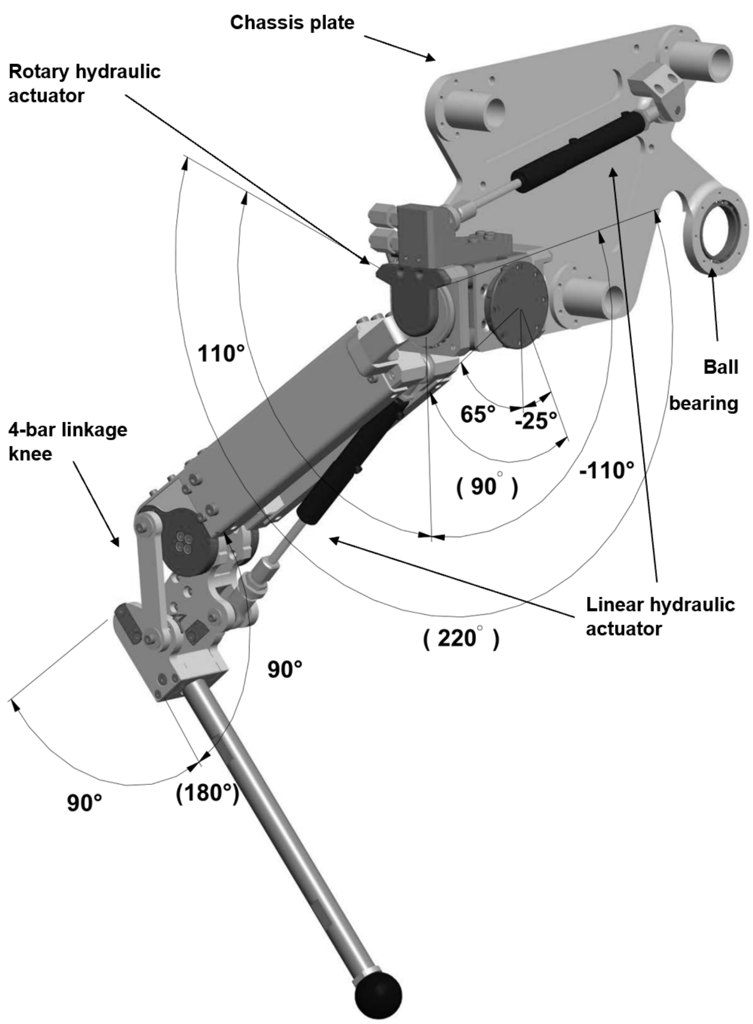

Figure 9: MiniHyQ Series-articulate leg topology [7]

Hip adduction-abduction, shown in Figure 10, is actuated via a Fluitronics AZ013 linear hydraulic actuator that connects the chassis to the rotary hydraulic actuator responsible for hip flexion-extension [7]. The attachment methods are not explicitly stated; it appears to be mounted via bearings to the chassis and rotary actuator.

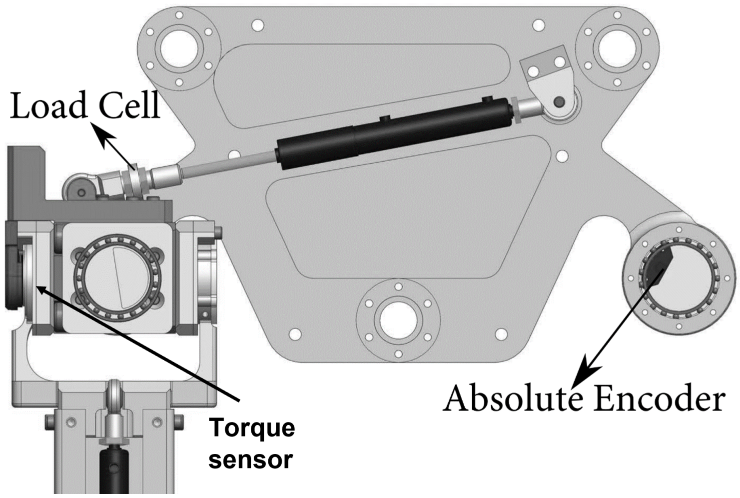

Figure 10: MiniHyQ Hip abduction and adduction is performed via a linear actuator connecting the chassis to the rotary actuator responsible for flexion and extension [7]

Figures 11 and 12 demonstrate the knee linkage when fully extended (+90°). The 4-bar configuration shown in Figure 11 allows for a 180° joint range, superior to the 120° found on BigDog and other preexisting hydraulically actuated models [6]. This allows for a greater range of motion and obstacle navigation, as well as the ability to self-right if fallen over. Compared to HyQ, MiniHyQ has a 40% wider joint range of motion in the sagittal plane. Although not explicitly stated by the author, individual linkages are likely attached with a set of bushings at the joints, similarly to how it is done with the Stanford Doggo [10].

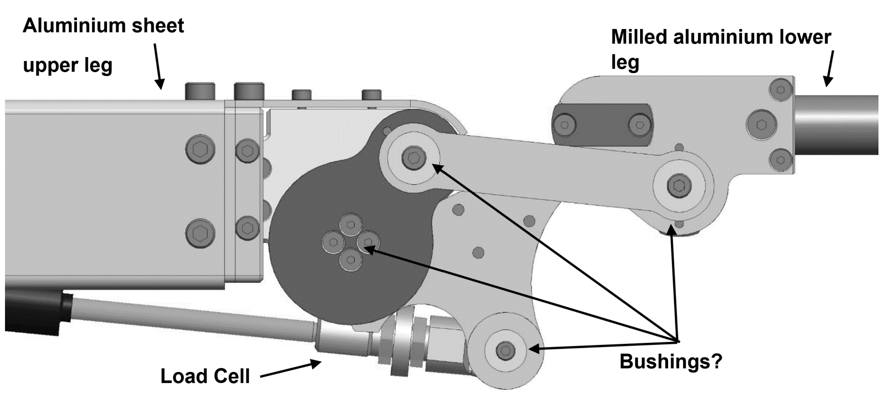

Figure 11: MiniHyQ 4-bar linkage for knee joint [7]

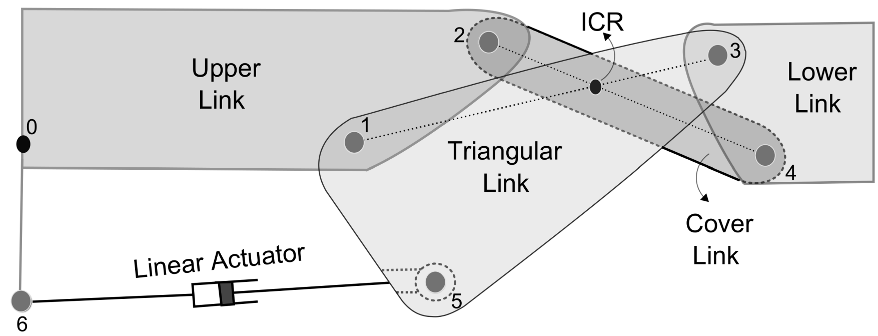

Figure 12: MiniHyQ 4-bar linkage for knee joint kinematics [7]

2.4.1.2 GOAT

GOAT is an omni-directional leg morphology inspired by mountain goats [8]. Each leg contains 3 Tiger U10 brushless DC motors and single stage Matex 1:7 planetary gear stages, shown in Figure 4. The author compared the performance of direct driven, quasi-direct driven, geared drive and series-elastic actuator driven actuators; the geared drive configuration for a single motor is shown in Figure 13

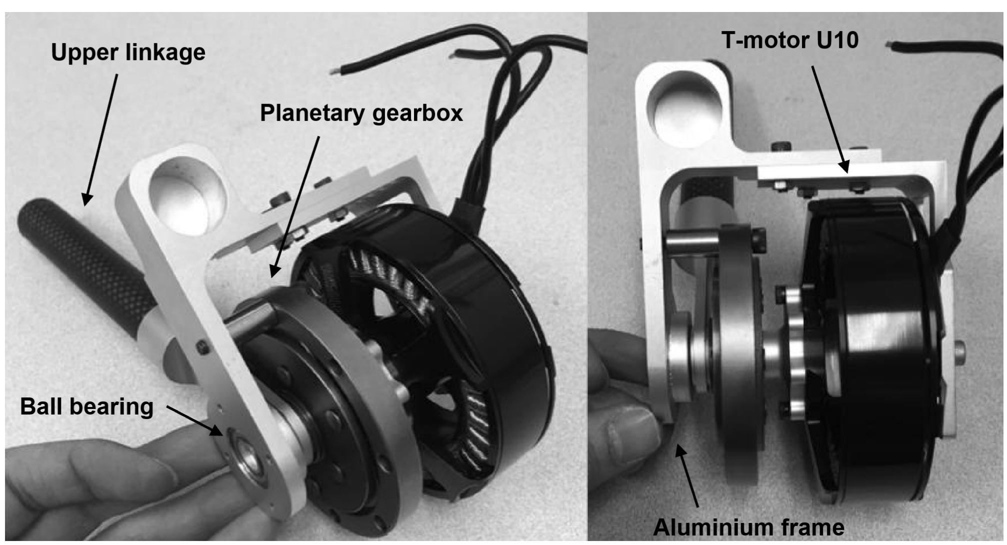

Figure 13: GOAT single motor and planetary gearbox [8]

The knee joint shown in Figure 14 are composed of two ball bearings in the upper thigh, one needle bearing in the knee and two more ball bearings below the knee. The centers of rotation intersect to simulate a spherical joint. This allows the GOAT knee to rotate with 3 DOF, but with a much greater range of motion for the compound joint (90° for the single needle bearing and 360° for the other two sets of bearings), improving the work-space of the leg [8]. There is a singularity when the axes of the lower and upper leg align, removing a degree of freedom, however this is only achieved when the leg is virtual straight. Carbon steel (1144) was used instead of aluminium for the bent knee piece as Von-Mises stresses exceeded aluminium's yield strength during hopping. Aluminium was used on the upper knee joint. 45558-HM Rockwest Composites carbon fibre rods are glued to the joints using Loctite Hysol E-120HP adhesive bonding.

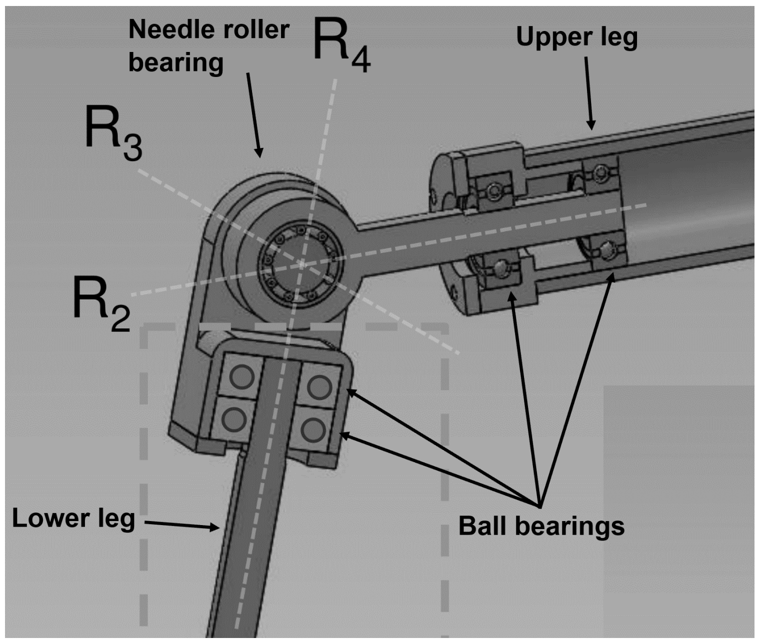

Figure 14: GOAT knee bearing configuration. Together, they mimic a spherical joint [8]

2.4.1.3 Stanford Doggo

The legs of the Stanford Doggo are simple linkage mechanisms, providing 2 DOF. These consist of one axis of rotation at the hip, and the extension of the leg. There is no second axis of rotation at the hip, which makes it slightly more challenging for this robot to turn. However, this can be achieved through using different leg speeds for the right and left side legs, similar to a tank. They are powered by quasi-direct drive motors. This means that they use a lightweight belt drive instead of heavier planetary gears which are often employed in legged robots, such as the GOAT. This minimizes the inertia of the robot when attempting quick and high jumps, while also providing a high torque [10]. The components of the leg system are shown in Figure 15. Two motors are used with belt drives to power coaxial drive shafts. These shafts each control the movement of one of the two upper leg linkages.

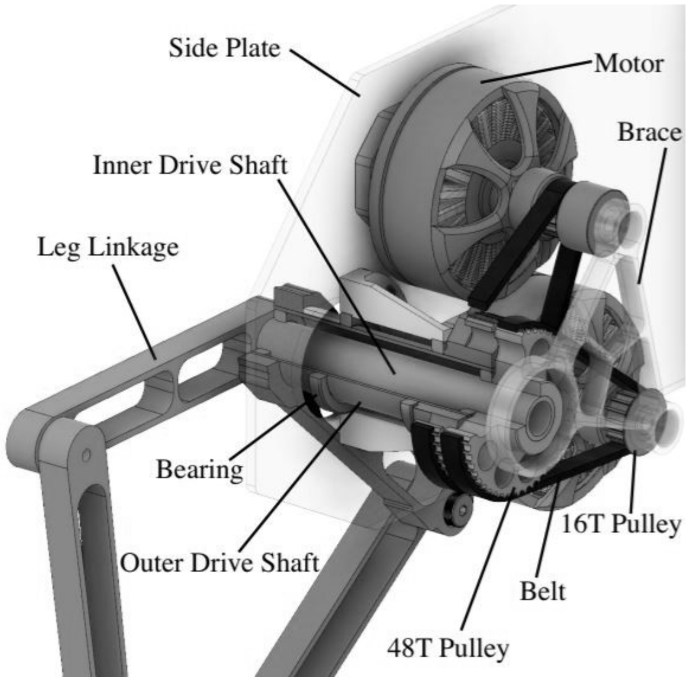

Figure 15: Stanford Doggo leg and quasi-direct drive system components [10]

2.4.1.4 CNC Hexapod

The CNC Hexapod employs a fairly common topology allowing for 2 DOF around the hip and a single degree at the knee, all actuated by miniature servos and fastened using screws [11]. The foot is attached to the leg via ball joint and uses gravity to retain its orientation. The design is based on the Phoenix Hexapod of Lynxmotion, and trades aluminium links for perspex ones. The hip configuration is very similar to the one found in Figure 42. The leg is shown in Figure 16.

2.4.1.5 Hexapod v2.1

Each leg of the Hexapod v2.1 is driven by three independant servo motors to offer a total of 3 DOF per leg [13]. The 3D printed links are first joined together using snap-fit connections and then secured using fasteners, as shown in Figure 17. The output shaft of the servo motor is press fitted by hand onto the joint part. The opposite side joint is simply connected to the link with a small cylinder pin. The servo motors' housings only offer limited protection against harsh environments. This assembly has the advantage of being small, lightweight, and sufficiently sturdy for its application as a hobby or toy.

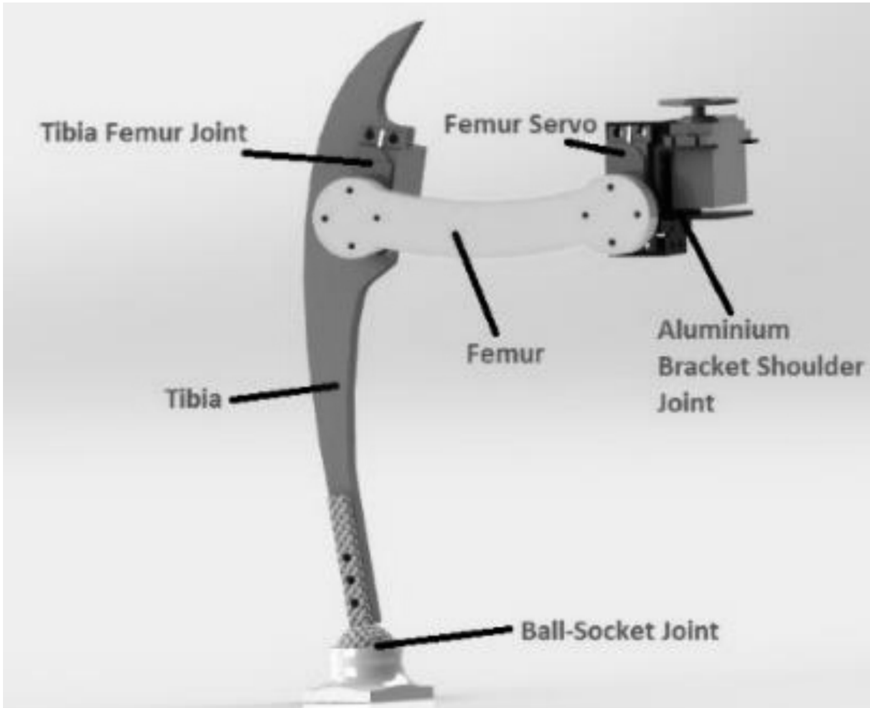

Figure 16: CNC hexapod leg morphology [11]

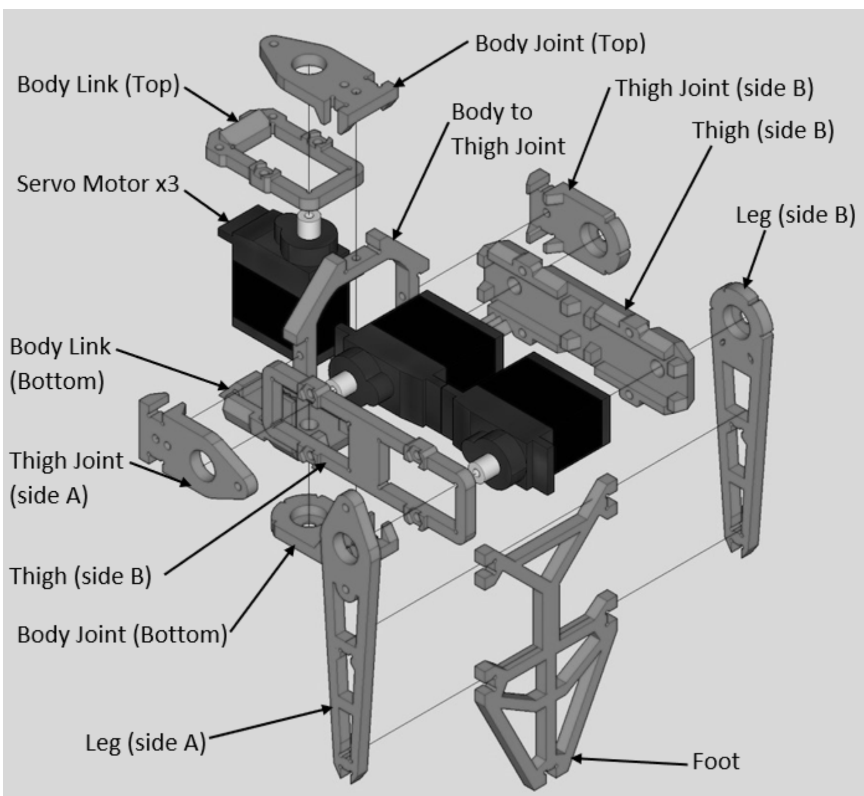

Figure 17: Hexapod v2.1 leg assembly components [13]

2.4.1.6 CRABSTER200

The CR200 robot's locomotion is composed of four watertight dedicated legs and two arm-combined legs. The arm-combined legs have the same design as the dedicated legs with the addition of grippers to manipulate tools. As the leg assembly is complex, Figure 18 illustrates a simplified diagram of the joints' DOF for both types of legs. The hip yaw joint is mainly responsible for the forward propulsion of the hexapod. On the other hand, the hip roll joint and the knee roll joint are used to lift each leg from the ground to continue its gait. A 3 DOF leg, as used on the previous Hexapod v2.1, provides sufficient stability, but a fourth DOF within the hip pitch joint gives more flexibility to the CR200 for climbing and generating downward force when facing high tidal currents [15].

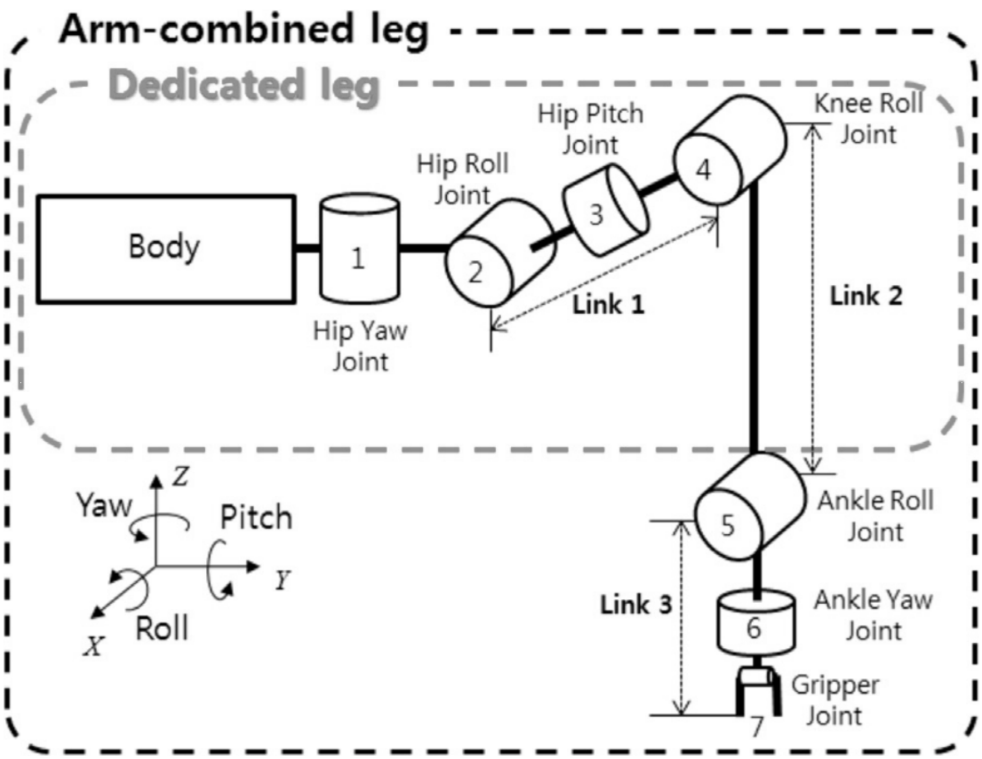

Figure 18: Dedicated and arm-combined leg joint schematic [15]

Each dedicated leg joint is driven by a 640 W frameless BLDC motor that offers a maximum torque of 8.4 Nm [15]. Each joint is also equipped with a harmonic drive gear set to transfer the reduced motion from the motor to the link, as shown on Figure 19. Magnetic and optical incremental encoders are used to help control the motors while absolute encoders are used to track the angular position of each link. For the hip jaw joint, the input shaft is supported by a ball bearing on each side of the motor. The output shaft link is mounted on two ball bearings at the drive end of the link shaft and on a single ball bearing at the other end of the hip roll joint housing. In a similar way, the hip roll joint's input and output shafts are mounted on a single ball bearing on each side of the motor for a total of four bearings. Again, the idea remains the same for the hip pitch joint and the knee roll joint: both input and output shafts are mounted on two ball bearings distributed on each side of the motors, with the exception of the hip pitch joint's output shaft that has its two bearings on the external side between the input and output ends.

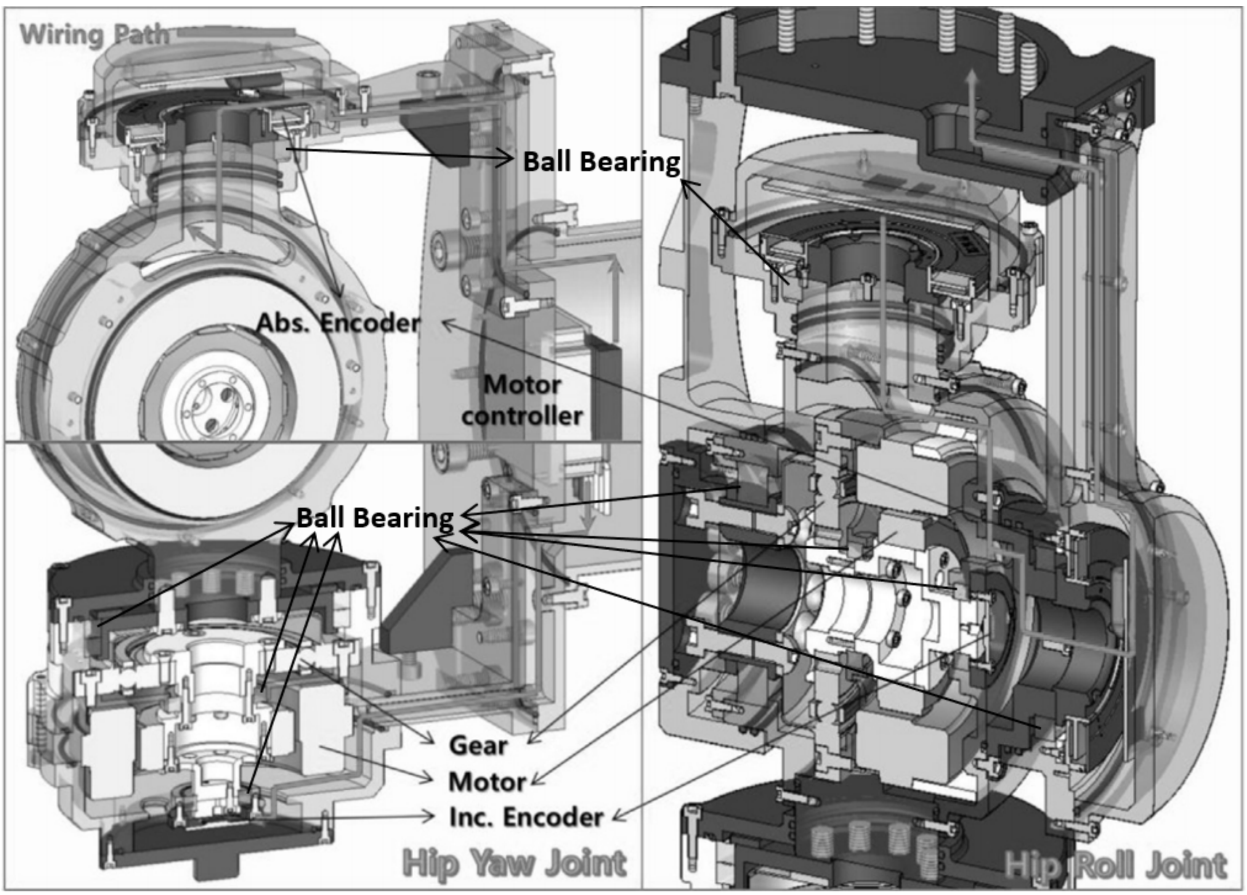

Figure 19: Hip yaw and roll joint structure design (image best viewed in colour) [15]

The watertight property is ensured with the use of single nitrile rubber type O-rings for flat contact surfaces and dual nitrile rubber type O-rings for cylindrical contact surfaces between two external housings as shown on Figure 20 [15]. The pressure-resistant and watertight housings of the motors, reduction gears and sensors were tested in a hyperbaric test chamber with a pressure of 25 bar [15].

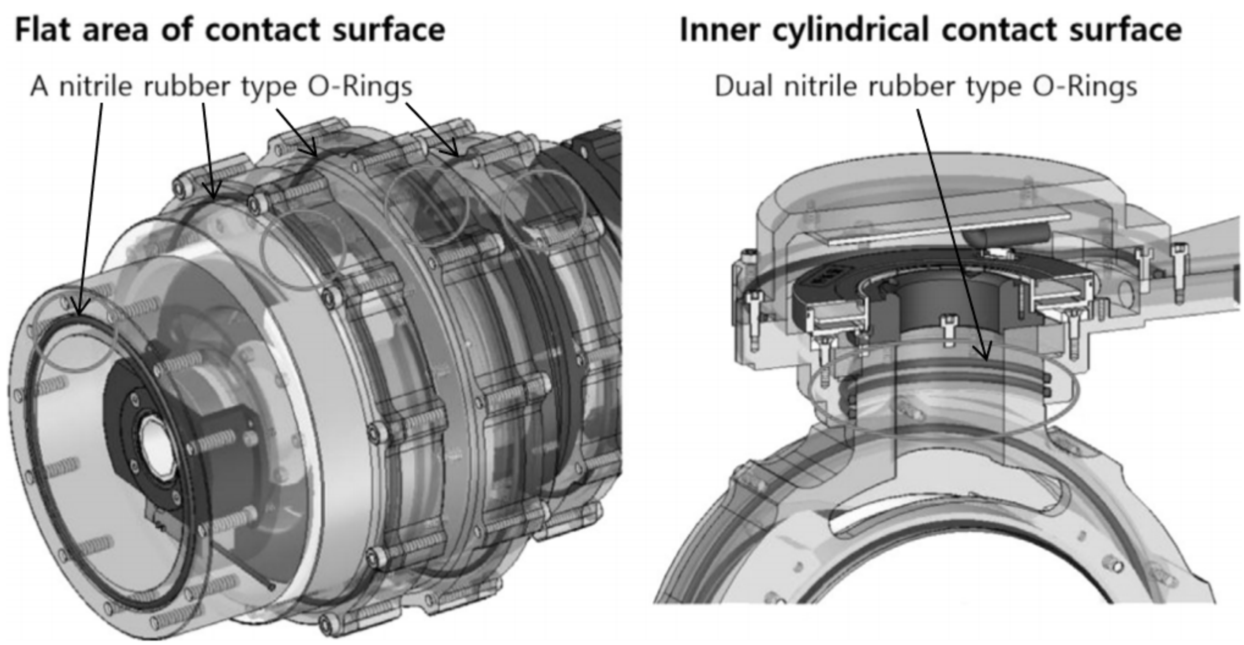

Figure 20: The waterproof design with O-rings (image best viewed in colour) [15]

2.4.2 Feet and Grip

Most quadruped robots rely on high friction ball-shaped polymer feet. GOAT, for example, has a half-sphere shaped foot coated in urethane rubber (see Figure 4). As well as providing friction during motion, the coating also acts as a mechanical damper and filters out high frequency vibrations [8]. Stanford Doggo uses Dragon Skin silicone rubber to cover the cylindrical feet shown in Figure 15 [9]. The CNC Hexapod leg shown in Figure 16 uses a flat foot and ball joint to keep it parallel to the ground [11]. MiniHyQ does not specify how their foot functions, but from casual observation it too seems to simply be some solid rounded shape with rubber/polymer coating [7]. Similarly, CR200 does not specify the material used for the foot that makes contact with the ground. Each of its leg is equipped with a load cell with a thin cylinder plate that makes contact with the actual foot component [15]. The leg from Figure 21 seem to be covered by an aesthetically designed casing with a round tip to imitate the anatomy of the crab legs. Hexapod v2.1 does not rely on any particular foot shape which is most likely due to its negligible weight and its unique purpose of being a hobby robot.

The challenge with a robot operating in rugged sandy or rocky beaches will be to ensure the feet do not dig into the ground excessively or get stuck. This could cause the robot to

Figure 21: Appearance of CR200's foot [15]

use more energy to move its legs due to the extra weight of the sand. A solution to this problem is applied in the use of snow shoes. These distribute weight on a larger area, thus decreasing the pressure applied on the snow surface, to limit how much a foot digs into snow [16]. Snow shoe frames are also often made open, to limit accumulation of snow over-top. It is a similar method to the morphology of camel feet, which have developed to walk on desert sand. Their feet are composed of two closely located toes and are very soft, with thick leathery soles. This provides cushioning, as shown in Figure 22 which causes the feet to expand when stepped on, giving a larger surface area [17].

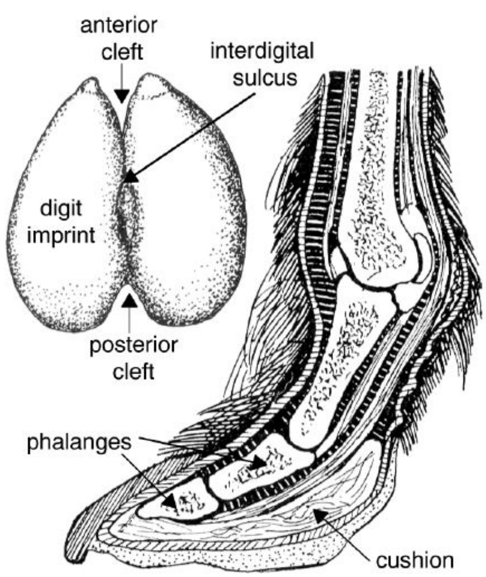

Figure 22: The anatomy and print of a camel foot. [18]

2.4.3 Chassis

Most existing quadruped and hexapod robots use aluminium sheets for their body (as found in MiniHyQ), or a combination of Aluminium sheets and Carbon Fibre sheets (as found in Doggo) [7] [10]. They are assembled using regular fasteners and standoffs for electronics. They are usually semi-open cases, which allow for optimal air-flow. The Doggo chassis is shown in Figure 23; standoffs, fasteners and electronics are visible.

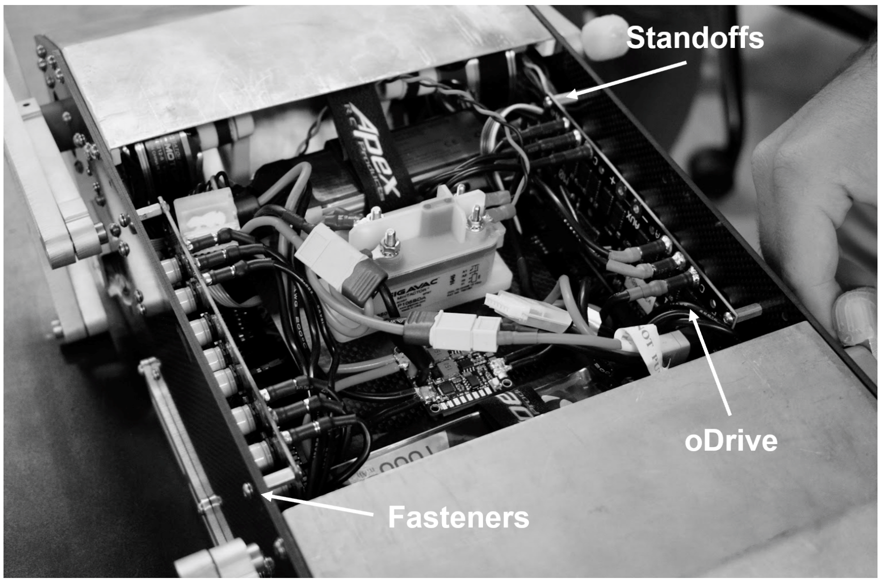

Figure 23: Stanford Doggo chassis and components [10]

Typical mounting of components to a robot chassis includes the use of bolts, washers, and nuts as shown in Figure 24 where two servo motors are mounted on a side plate. The same technique can be used for mounting power and computing equipment.

Additional plates and brackets can be mounted using standoffs and bolts as shown in Figure 25; in this figure an additional metal bracket is added for supplemental mounting capabilities. Furthermore, mounting brackets such as multi purpose brackets, servo brackets, U brackets, L brackets, C brackets, pan brackets, tilt brackets, plates, rails, angles, channels and custom designed brackets can use similar mounting procedures.

These designs, although simple, are insufficient for a waterfront environment, as they allow water, dust and other objects to enter. The designs must thus be enhanced to meet weatherproofing standards. IP67 gives complete protection against dust and contact, as well as immunity to water jets and immersion in 1 meter of water. Since the robot will operate on a beach and potentially in shallow water, this rating is appropriate [20]. The equivalent NEMA rating, Type 6, can be achieved with the following enclosure considerations [21]:

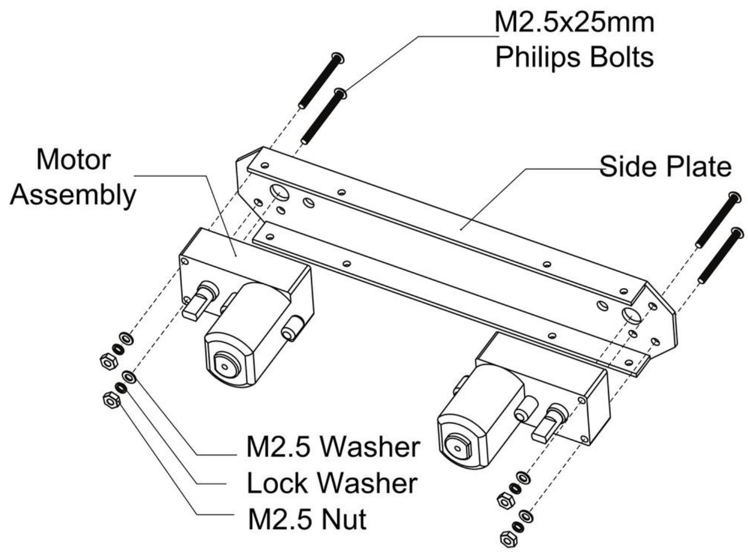

Figure 24: Basic mounting procedure to a metal plate [19]

- Overlapping flanges on open seams
- Minimal number of seams
- Gaskets and O-rings at openings/joints
- Fasteners with included O-rings
- Even torque to screws for even O-ring/gasket compression
- Tight screw placement for even gasket pressure

An example of a waterproof hull and shell design mounted to interior plates, brackets and frame is shown in Figure 26. This type of structure can be used to mount all electronic components on non water-resistant materials and conceal all equipment by mounting an exterior shell made of weatherproof materials and sealed to water, dust and sand particles.

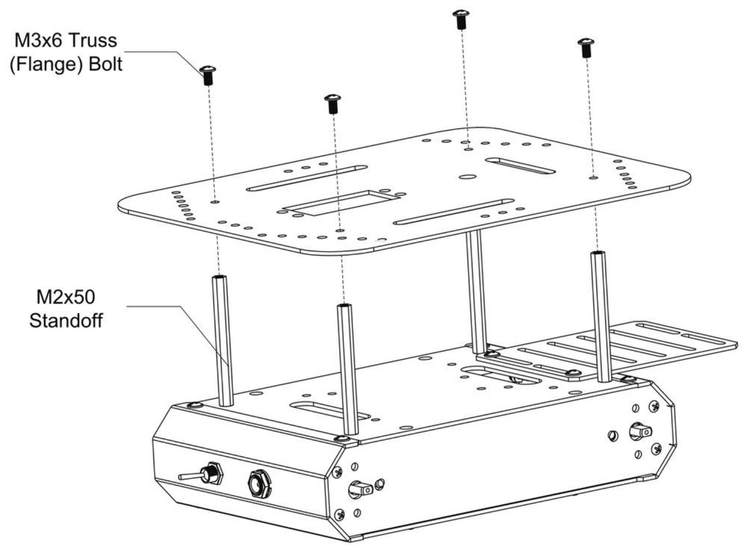

Figure 25: Mounting of additional mounting plates [19]

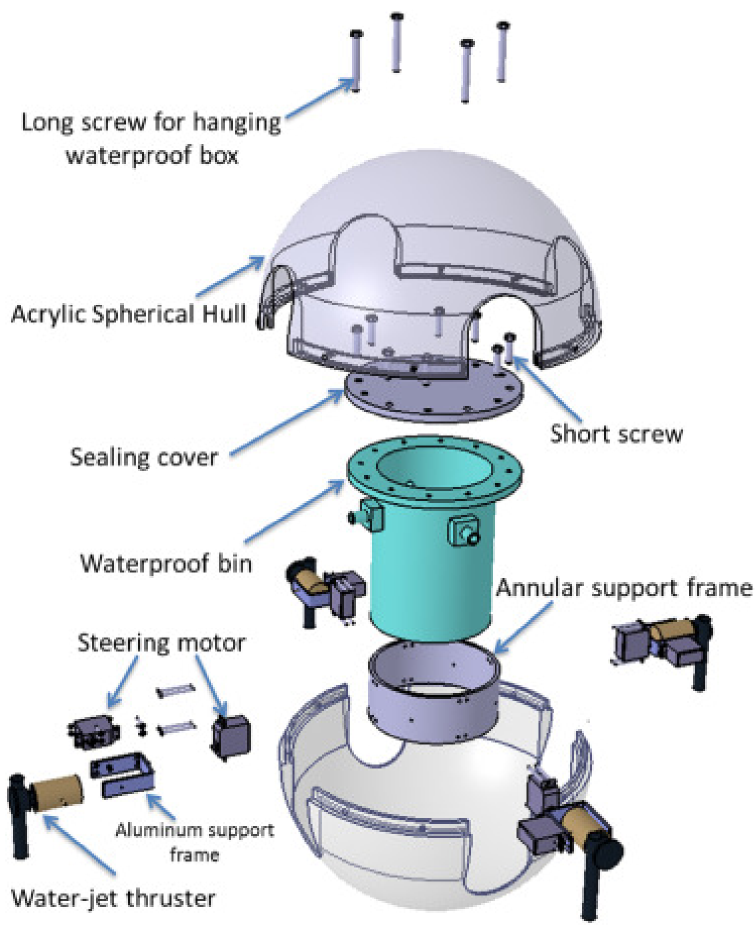

Figure 26: Waterproof shell mounting [22]

The CRABSTER200 shown in Figure 8, partially satisfies these watertight constraints. The mechanical components and housings of the CR200 hexapod are made of aluminium 6061 for easy fabrication while the chassis is made of a carbon fiber reinforced polymer (CFRP) composite and the shell skin is made of a glass fiber reinforced polymer (GFRP) composite [15][23]. In this case, the hull has an opening in the front for the too sled and therefore is not watertight, but the components within the body are well sealed with gaskets and O-rings [15].

2.4.4 Power System

In order to be self-reliant and operate in remote areas, the waterfront robot must use a solar power system to generate the necessary power for its activities. A basic solar system consists of photovoltaic solar cells generating DC power which is fed through a regulator. This regulator ensures that the batteries do not get damaged. In the case where AC power is required, an inverter is used [24]. These components are shown in Figure 27.

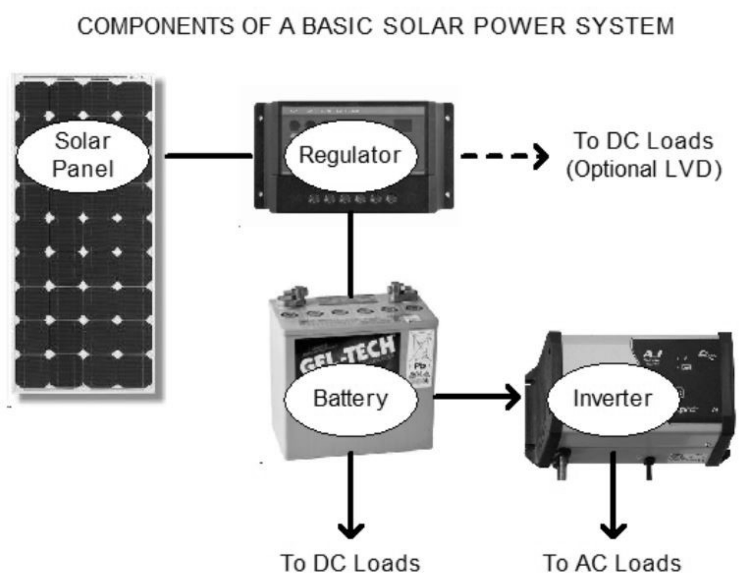

Figure 27: Solar panel system components [24]

To give an approximate idea of the specifications of solar panels, suggested off-grid RV solar panels were found by Wholesale Solar. A 100 W rigid solar panel (SLP100-12U) weighs 8.9 kg and has a surface area of 0.72 m^2. It is composed of 36 solar cells [25]. Technical specifications are provided in the Appendix A.9. The panel's weight is considerable for a robot to hold, and is almost twice the weight of the Stanford Doggo [10] mentioned previously.

Considering this robot can operate at 840 W, one 100 W panel may also not be sufficient to maintain a reasonable operation time or speed. The energy collected by the solar panels would be stored in the battery which would allow the robot to work. However once the battery is depleted, the solar panel alone would not be sufficient. The robot might thus require to take battery charging breaks during the day. Rigid solar panels can be mounted to a surface using a rack with clamps. An example of an assembly is shown in Figure 28 [26].

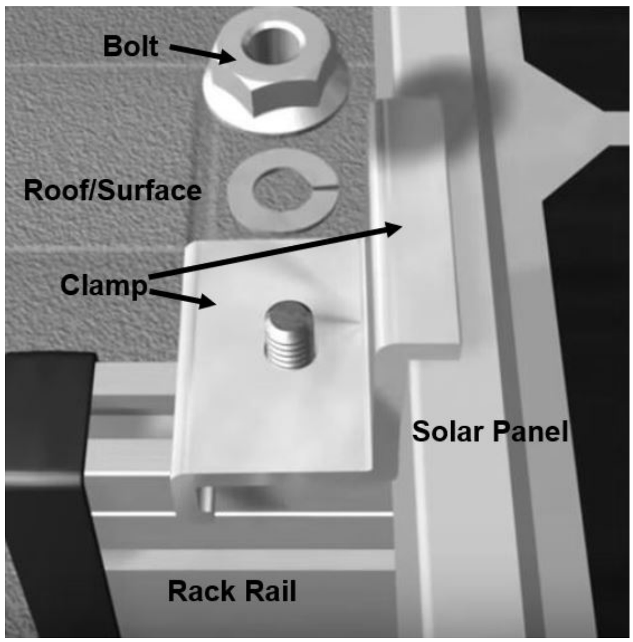

Figure 28: Rack mounting system for rigid solar panels [26]

Another option would be to use flexible solar panels. A 100 W model (SPR-E-Flex-110) recommended by Wholesale Solar for RV's (comparable to the previous rigid solar panel shown) weighs only 2 kg and has a surface area of 0.64 m^2. It contains 32 solar cells [27]. The small weight of the flexible solar panel compared to the rigid type could contribute to a better efficiency of the robot system, as a small weight takes less energy to move around. Technical specifications are provided in the Appendix A.9. This type of solar panel can be bent up to 30 degrees and is better adapted to rugged environments [28]. They are easily mounted flush onto a flat or curved surface using adhesives or grommets integrated onto the sides of the panel [27]. Figure 29 shows how to use a bolt kit to mount the flexible panel on canvas [29]. This method could be used for other thin mounting surfaces as well.

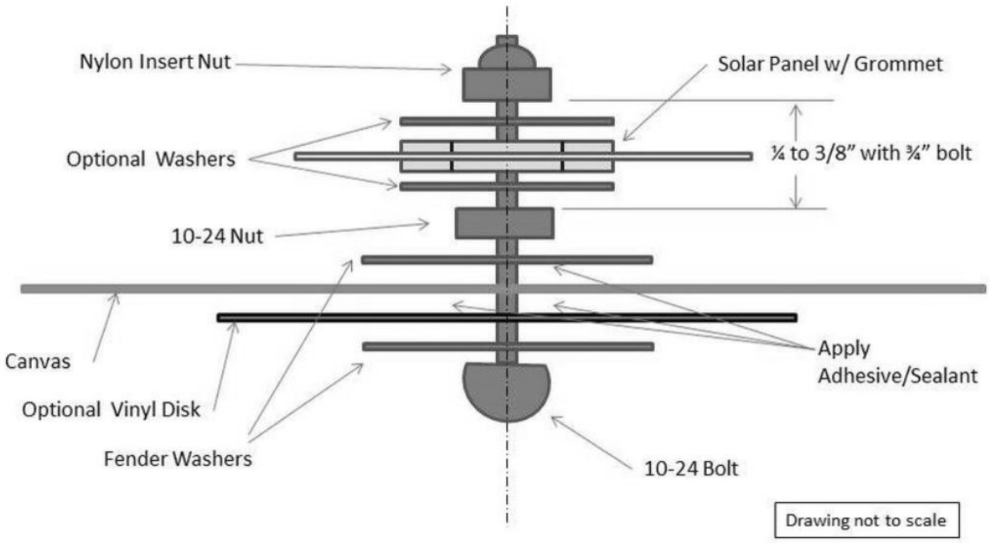

Figure 29: Bolt mounting for flexible solar panels onto canvas (or other thin materials) [29]

Due to the mobile and rugged nature of the application, a more custom solar system solution may be required. It is possible to obtain custom solar panels from many providers such as Voltaic Systems [30] and Hovall [31]. The required dimensions, shapes, connections, specifications and more can be accommodated. It is also possible to obtain solar cells on their own (not made into a panel). A very efficient flexible solar cell, the MAXEON, is available from Sunpower. These cells each weigh 6.5 g and have dimensions of 125 X 125 mm. Their peak power output is of about 3.54 W [32]. More details are provided in Appendix A.9. Tabs weighing 0.3 g each are used to attach the solar cells together (these are mentioned in the solar cell specifications in the appendices). By comparing the area of the previously mentioned flexible solar panel (recommended by Wholesale Solar [27]) with the equivalent area in these solar cells (while also taking into account space for connecting tabs), it is estimated that they would provide about 125 W in power, instead of only 100 W.

As mentioned previously, a solar regulator is required to regulate the power going to the battery. It is chosen based on the amount of amperage that it can accept from solar panels. Thus, it should be able to accommodate the sum of the maximum current of all the solar panels in the system. It is also best to increase this number, as in ideal conditions, a solar panel could produce slightly more energy than specified [33]. Both the previously mentioned panels (rigid and flexible panels) have a maximum current of about 6 A [27] [25]. Assuming that the robot might require two or more 100 W solar panels, a 20 A regulator (SRP0240) was found from REDARC Electronics. It weighs only 0.26 kg and has dimensions of 153 x 76 x 37 mm [34]. Additional specifications are shown in Appendix A.9. It can be easily mounted on a surface using fasteners, as shown in Figure 30.

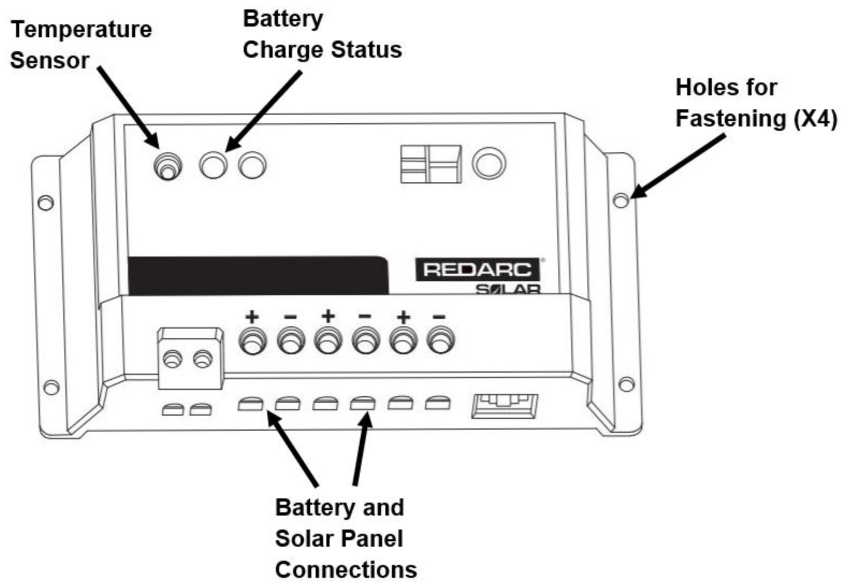

Figure 30: Configuration and mounting of a regulator by REDARC Electronics [34]

2.4.5 Drive System: Motors and Gear Reducers

Electrical motors are separated into two main categories: AC and DC motors, with DC separated into brushed and brushless motors. The differences between an AC and DC motor, apart from their input current type, is the efficiency, service life, and operation.

As DC motors use permanent magnets, less energy is lost in the creation of electromagnets and will provide flat torque over wider speed ranges compared to AC motors [35]. However, AC motors tend to have higher life expectancy than DC motors [36]. Brushless DC motor will have a higher efficiency compared to brushed DC motors due to the absence of friction [35][37]. See specifications sheet in appendices. Common DC motor manufacturers include Maxon Motor and T-motor; the former develops stepper motors designed for industry and robotics [38]. Their power consumption is between a Watt and 500W, output torques up to 1 Nm without gearing, and diameters between 6 and 90mm [39]. T-motor develops DC motors for multirotor and fixed wing aircrafts [40]. Stanford Doggo and Simon Kalouche's GOAT both use T-MOTORS to actuate their legs, along with belt drives and planetary gearboxes [8] [9]. Their motors scale from a few watts to 10 000W for their largest unit. Because they are not stepper motors, a special motor driver is required to manipulate them to precise positions; in the case of GOAT, it is custom made, whereas Stanford Doggo leverages oDrives [41].

To operate at a motor's most efficient or nominal point, the output speed of the motor should be maximized and output torque minimized [7]. To achieve this, gear reducers are mounted on the output shaft to achieve a more usable speed (RPM) and torque level. Different types of gear reducers exist, such as planetary; parallel and right angle shaft; and worm gears [42]. Small planetary gears with 100:1 ratios are available for rated speeds between 3000 RPM and 5000 RPM. They are priced at 70 to 200 CAD depending on the size of the shaft or NEMA type [43]. Even smaller gears can be found with reduced ratios when applicable; for example, the Matex 7:1 planetary gearbox used by GOAT weighs 0.2 with a 7:1 ratio kg[8]. Matex's smallest metal offering has a 3:1 ratio, measures 25mm in diameter, 13mm in depth and weighs 20g [44]. Gear boxes are mounted using the designated mounting holes, and a shaft coupling mechanism. As shown in Figure 31, the gear reducer is mounted using 4 screws and bolts, and the shaft coupling uses a keyway.

Figure 31: Planetary gear box with mounting points [43]

2.4.5.1 Gear Motors

Gear motors are a combination of motor and gear reducer. They vary in shapes, sizes, weight, power, and speed.

The type and direction of the output shaft can vary. As shown in Figure 32 the output shaft can be parallel or perpendicular to the motor, and the shaft can be hollow or solid.

Figure 32: Output Shaft types and configurations. [45]

Gear motors come with multiple mounting configuration types. Figure 33 illustrates two configurations: flange mounting and foot mounting.

Figure 33: Flange (Left) vs. Foot (Right) Gear Motor Frame Mounting. [46]

The Figure 34 illustrate how the foot mounting configuration can be used to position the gear motor in multiple different configurations.

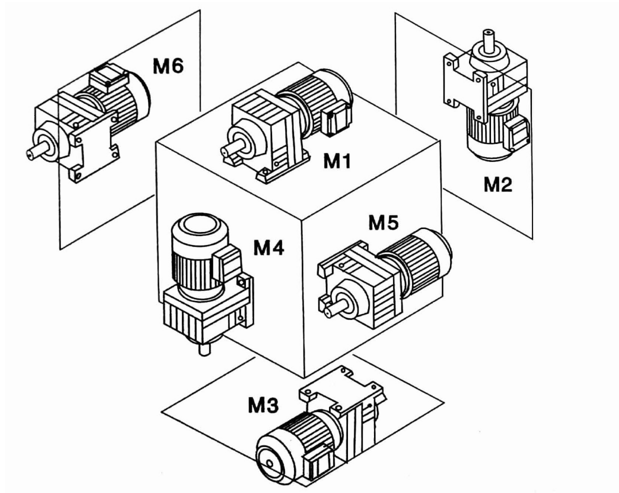

Figure 34: Multiple positions of a gear motor using frame foot mounting. [47]

Using the flange mounting (or front hub), allows gear motors to be mounted to L bracket as shown in Figure 35, or to other types of brackets, panels, and channels. The advantage to mounting gear motors to brackets is the height adjustment configuration provided by the bracket. Figure 35 illustrates three possible height adjustments using a specific L bracket. The multiple mounting holes enable the height adjustment configurations.

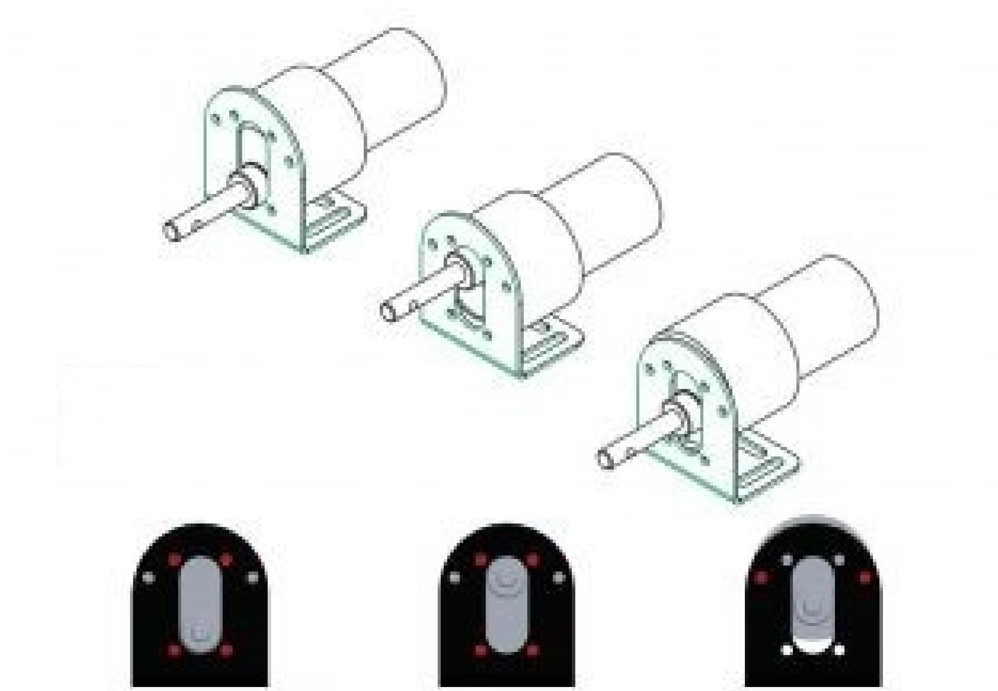

Figure 35: Multi-height L bracket mounting capability [48]

Gear motors operating at 0.6 RPM with 12 Volts DC power, 5.65 Nm torque and 1.2 W are available from McMaster-Carr [49]. They have dimensions of L: 3.25 in, W 2.75 in, H: 3 in, and sell for 62.74 USD each.

More heavy duty gear motors are also available from Acklands Grainger [50], reaching 80 Nm at 1.3 RPM, 90 Volts DC and 27 Watts. They have dimensions of L: 10 in, W: 2.58 in, H: 4.10 in and weigh 16.0 lbs. They are priced at 821.41 USD each. See specifications sheets in Appendices A.13.

2.4.5.2 Servo and Stepper Motor

Stepper and Servo motors are heavily used in robotic applications and applications where continuous rotations are not required. Stepper motors have more poles than servo motors, typically 50 to 100 poles, while servo motors only have 4 to 12 poles. Stepper motors are more accurate than servo motors as they can move accurately to their large quantities of poles. Servo motors require encoders to appropriately measure their current location; the servo motor will adjust according to the feedback response of the encoder. The drawback to having a large quantity of poles, such as for stepper motors, is the reduced torque at high speeds. However, at low speeds the motor will have higher torque capacity compared to a similar size servo motor [51]. Figure 36 depicts typical shape of a stepper and servo motor.

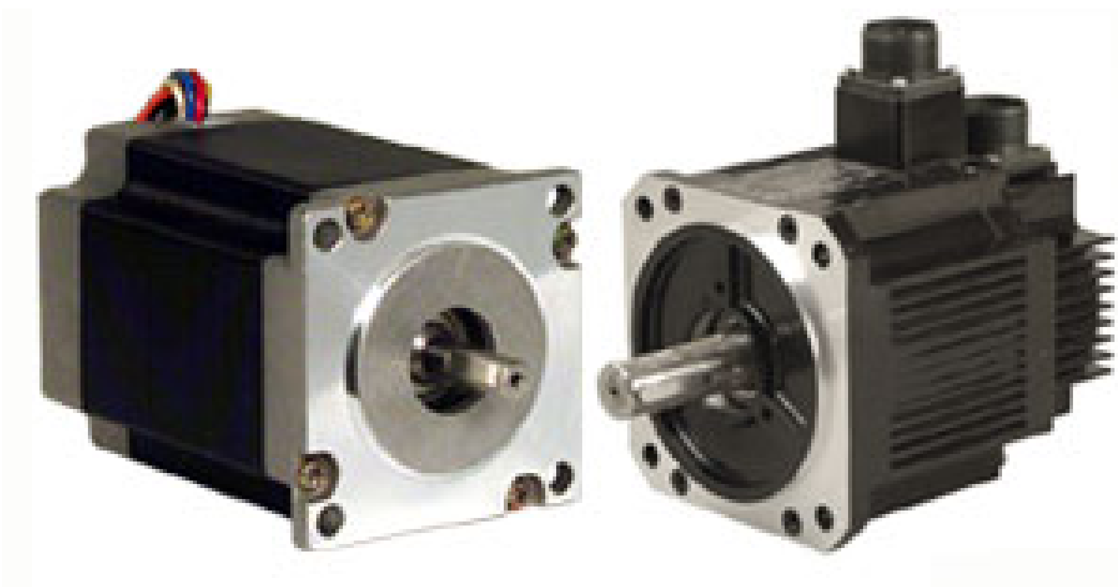

Figure 36: Stepper (Left) vs. Servo (Right) Motor [51]

The procedure to mount components to the frame can vary based on the component's manufacturer. As shown in Figure 37, the servo motor is manufactured with multiple mounting holes, enabling multiple mounting configurations.

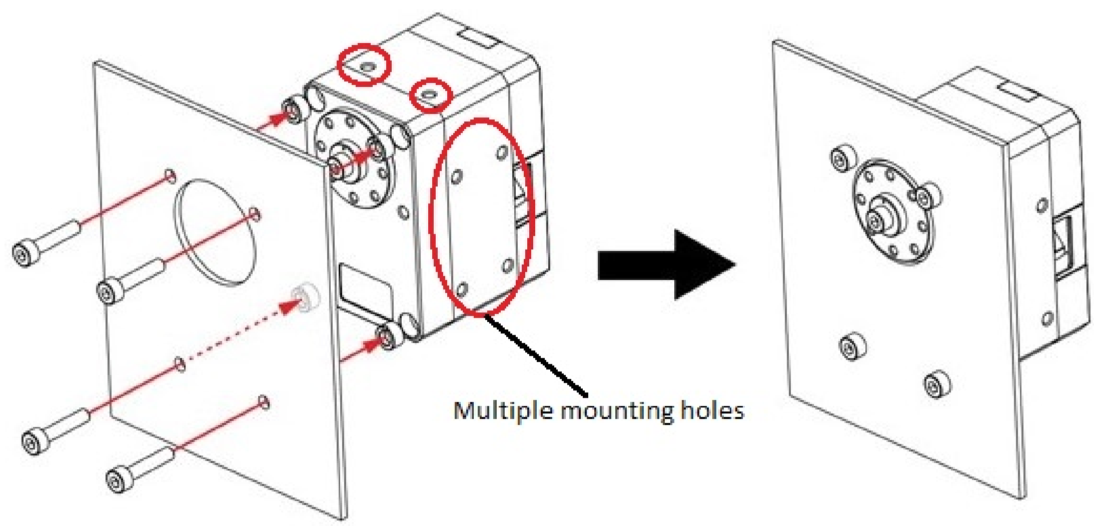

Figure 37: Multiple mounting holes [52]

2.4.5.3 Shaft Component Mounting

The mounting or coupling of the motor shaft to the bracket or frame is accomplished through the use of servomotor horns and mounting hubs. Mounting hubs and servo horns have different shapes and forms. However, their mounting mechanism to a shaft is very similar. The horn can be screwed to the spline of the output shaft as shown in Figure 38. Mounting hubs can be equipped with set screws to mount to the shaft as shown in Figure 39, keyways as shown in Figure 40, and other shaft coupling mechanisms. The mounting hub can then be linked to other mechanical components such as mechanical linkages, brackets, and more. Commonly, the components are screwed using the screw holes in the servo horn. Figure 41 depicts the mounting of a mechanical linkage to the servo horn using a screw, washer, nylon spacer and nut. The nylon spacer functions similarly to a bearing, by enabling the rotation around its axis.

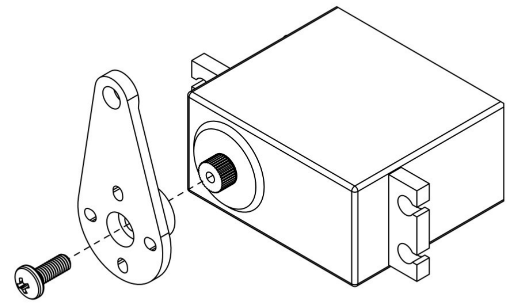

Figure 38: Horn assembly to servo motor [53]

Figure 39: Mounting hub with set screw [54]

Figure 40: Mounting hub with key way [55]

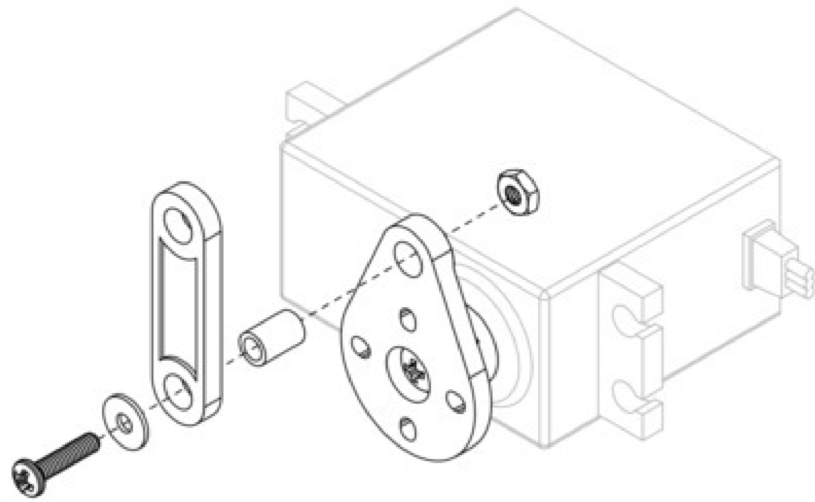

Figure 41: Mounting of mechanical linkage to servo horn [53]

A two degrees of freedom joint (such as for a hip) can be achieved using two servo motors and a mounting configuration similar to Figure 42. The assembly depicted in the Figure 42 uses a servo mounting bracket and a U shape mounting bracket. The first motor's horn is mounted to a servo motor bracket, the second servo motor is mounted on the bracket, and the second servo's horn is mounted to the U-shape bracket, achieving two degrees of freedom.

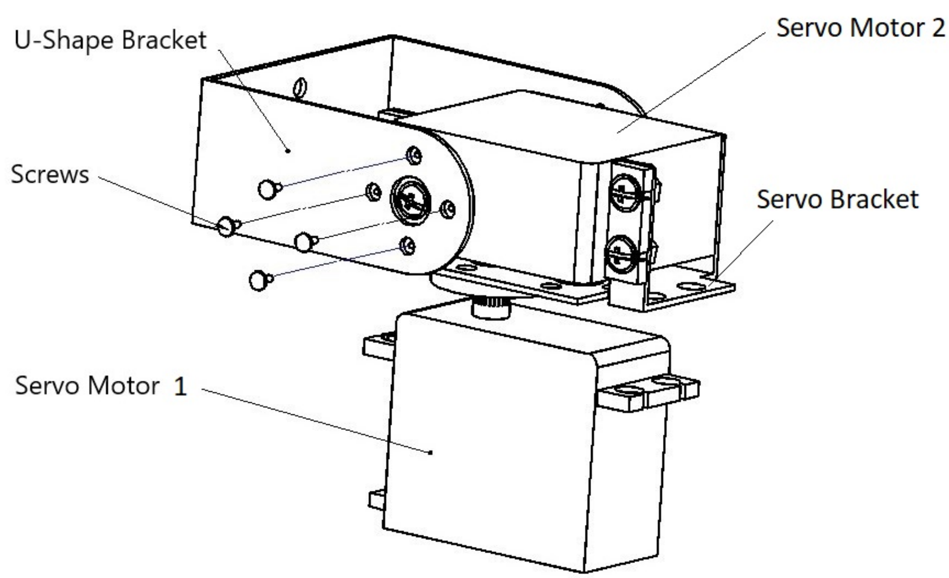

Figure 42: Multi-servo joint typical mounting assembly [53]

2.4.6 Drive System: Other System Types

Some other drive system options exist which do not fall under the motor and gearbox type. These include belt drive systems and hydraulic systems.

2.4.6.1 Belt Drive System

To transmit power and maximize torque, it is possible to use a belt and pulley system, as seen in the Stanford Doggo design [10]. The advantages of this type of system are that it can transmit power between widely spaced shafts, is low cost, is quiet and requires no lubrication [56]. Thus a custom belt drive solution could be useful in transmitting motion to all the legs of the waterfront robot if for example a single central motor was to be chosen. There are various types of belts that can be used, which are separated into two larger categories: friction drive and positive drive. Friction drive belts, such as flat or V-belts, rely on friction. Positive drive belts use teeth which mate with grooves on the pulleys. This allows the belt to keep a more constant speed, as it does not slip [57]. This may be required to maintain the full control of the waterfront robot. Figure 43 shows the basic components of a belt drive system, and how they are attached to a motor.

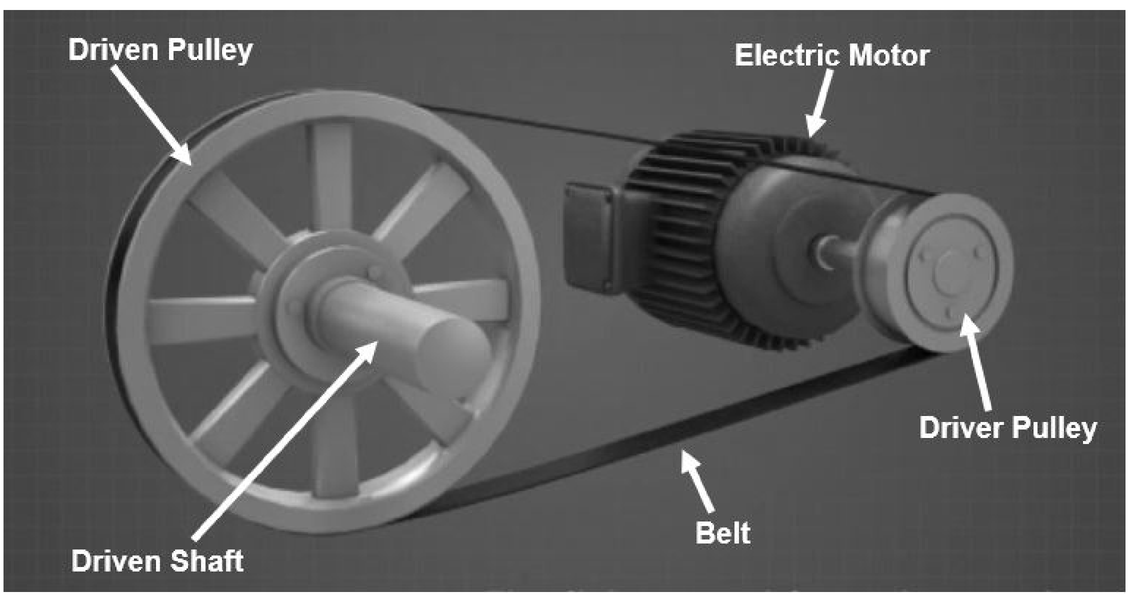

Figure 43: Basic components and integration of a belt drive system [57]

Bushings are used to mount pulleys and sprockets onto shafts. They are available in different formats, including sleeves, quick disconnect and tapper lock formats. Figure 44 demonstrates a flange bushing used to mount a pulley to a shaft. The bushing is coupled with the pulley using three screws and mounted on the shaft using a keyway.[58]

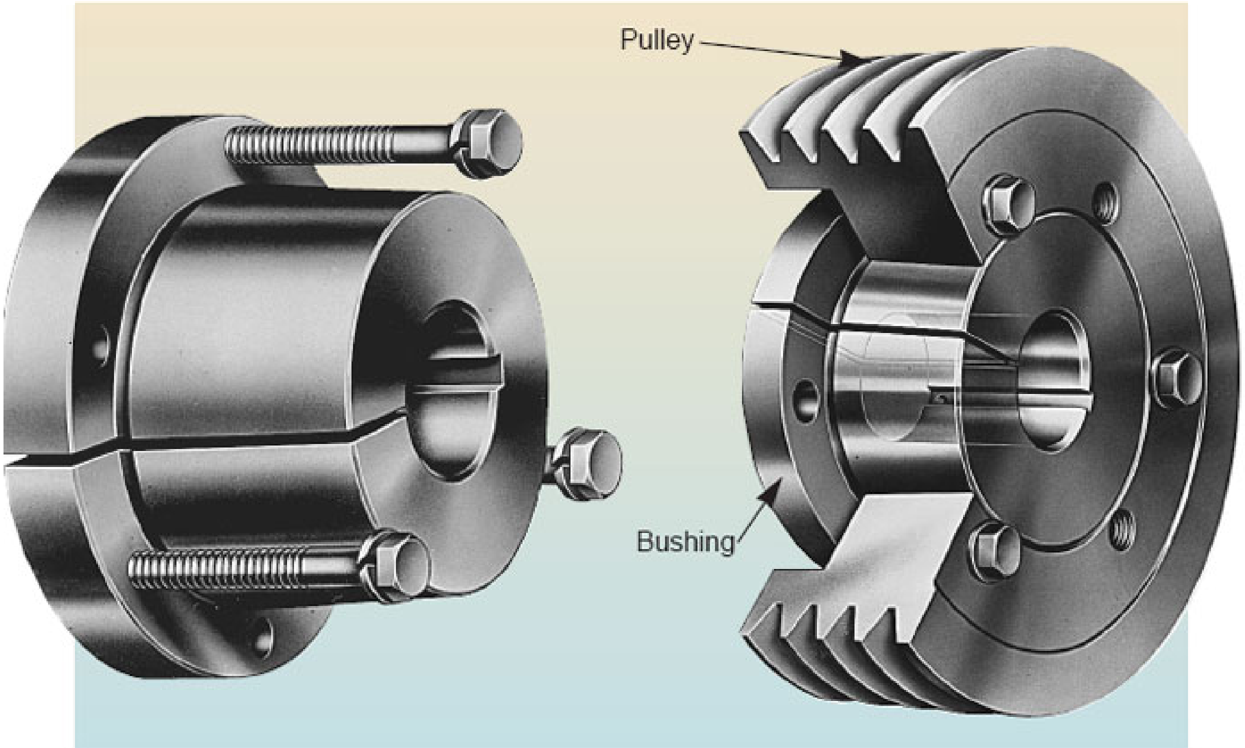

Figure 1 — Flanged bushings (left) have three mounting screws or more, except for light duty models, which have two screws. Pulley is mounted (right) by sliding it over the bushing hub and tightening the screws.

Figure 44: Bushing mount for pulley [58]

2.4.6.2 Hydraulic System

Hamza et al designed a compact hydraulic system capable of fitting on and actuating the MiniHyQ quadruped robot [59]. The system weight is proportional to supply pressure and flow; a reduction in leg velocity also reduces the system weight (a reduction that is amplified by the leg kinematic redundancy found in Figure 9) [6]. In the configuration found on MiniHyQ, the power pack occupies 0.59 X 0.2 X 0.19 m of the robots total 0.85 X 0.35 X 0.77 m, weighs 12 kg, has a 13 L/min peak flow rate (10 L/min rated flow rate), 20 MPa operating pressure and 5.5 kW power consumption [59]. The custom design is shown in Figure 45. It reduces the overall system weight down to 35kg, in contrast to the original HyQ robot's 98kg, for a similar frame size. Further details on hydraulic power systems can be found in the appendices.

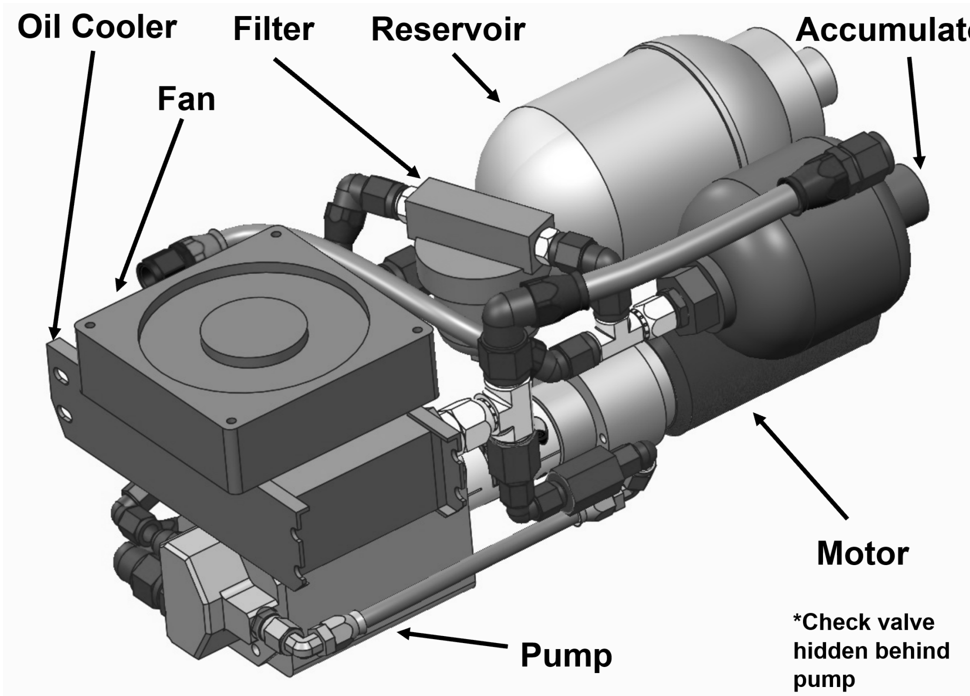

Figure 45: MiniHyQ on-board hydraulic system [59]

2.4.7 Cooling

Stanford Doggo consumes 840 W at peak; the larger hydraulically actuated MiniHyQ consumes 5.5 kW at peak at 4 times the volume [9] [7]. Proper cooling for the actuators and electronics is essential for maximizing motor performance [60]. It is achieved in these robots via passive heating; the robot chassis are open, allowing for airflow to the drivers, computer, and other electronics. The actuators themselves also have ribbed housings, improving their heat dissipation via natural convection by increasing the surface area exposed to the air. Both these design decisions are not suitable for a beachfront environment, as all components must be in watertight enclosures. The simplest solution, passive cooling, is not an option as heat will accumulate in the chassis until components overheat. Using fans to push heat away from high-power components will not work either, as this simply displaces heat elsewhere in the chassis, with the same result as before. If moving rapidly, a more well thought-out approach to cooling must be considered. It was indicated that cooling may not be a necessary design consideration, as the robot will be moving slowly and not output the thousands of watts seen in other dynamic robots. A detailed look at cooling solutions can be found in the appendices.

2.5 Standard mechanical components

2.5.1 Seals and Waterproofing

2.5.1.1 Static Seals for Enclosures

To provide a weatherproof chassis or enclosure, many components and methods can be used. The first is the use of O-rings in compression to seal elements such as fasteners or buttons. A sealing fastener with O-ring is shown in Figure 46. This is an adequate method to keep water and contaminants out of the enclosure [61].

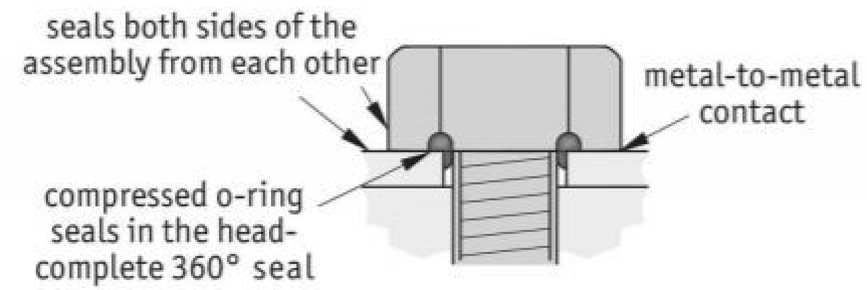

Figure 46: Possible gasket configurations and mounting [62]

O-rings often fall in the broader category of gaskets, which are compressible materials that can be added between parts. The compression is often achieved by a mechanical method such as bolting the parts together [63]. Gaskets are available in many shapes, sizes and materials, and can be custom made [64]. An example of available materials for custom made gaskets (from Protocase manufacturer) is shown in Appendix A.3. Some gasket mounting configurations are shown in Figure 47.

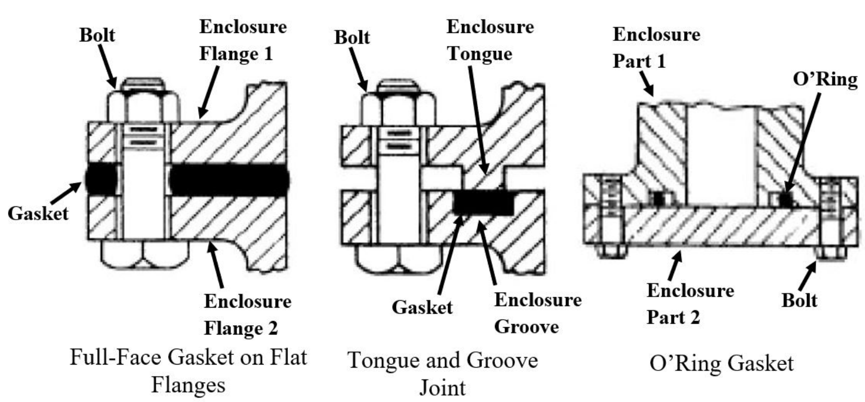

Figure 47: Possible gasket configurations and mounting [63]

An additional option is liquid sealants. These are used in a similar way as gaskets, but are applied in the liquid form onto the parts, and harden after the assembly has been completed. This allows them to take the shape of the gap. Generally the solidification is done through a chemical reaction, which can be anaerobic [65]. Their advantage is that they can be easily formed in the required shape, and can be re-applied if broken for maintenance purposes. Many materials, such as silicone, polyurethane and various polymer sealants are available. Each provide various properties, which can include resistance to marine environments and UV-radiation [66]. Figure shows the application of the liquid sealant, while taking care to circle around any fastener holes [65].

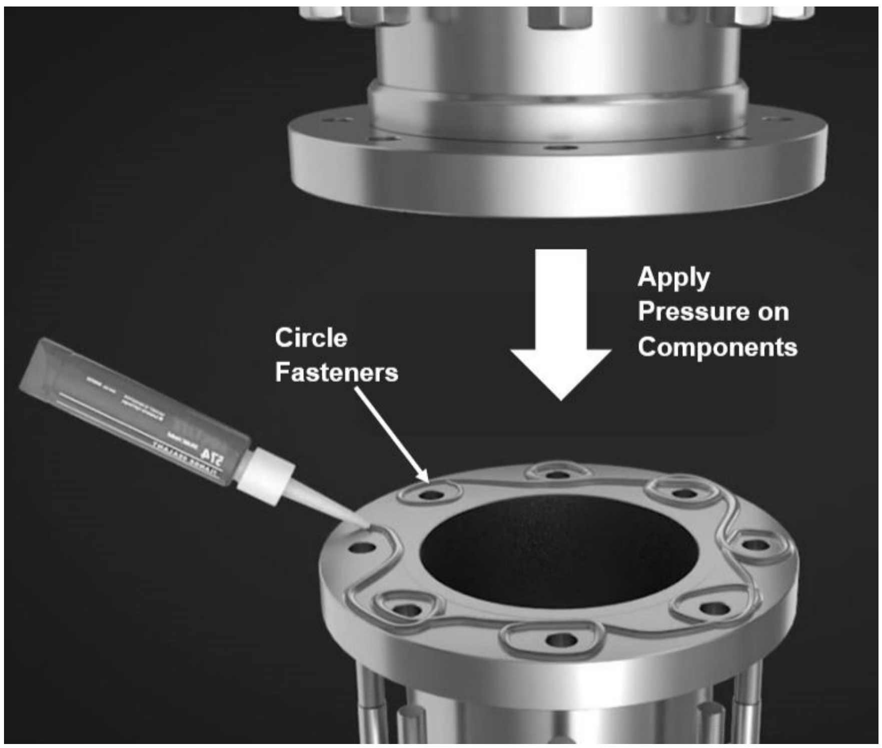

Figure 48: How to seal components using liquid sealant [65]

2.5.1.2 Dynamic Seals for Exterior Components

The waterfront robot could have sensible elements located on its exterior, for example on the legs. These must be protected from the elements using some form of barrier. "Interior" style rotary shaft seals and seals for reciprocating motion elements (such as pistons) are likely not to be used in this application as they are more useful for continuously rotating joints or are considered integral parts of off-the-shelf components. Some options and explanations are shown in Appendix A.7.

The focus is to shield expanding and flexible components such as linkages and moving joints. Molded bellows can be used to cover the assembly. They are available in many shapes and materials (including waterproof and custom options) and are often corrugated to provide angular and linear flexibility (see Figure 49). They can be mounted using hose clamps or by using a backing plate bolted to the assembly, as shown in Figure 50 [67].

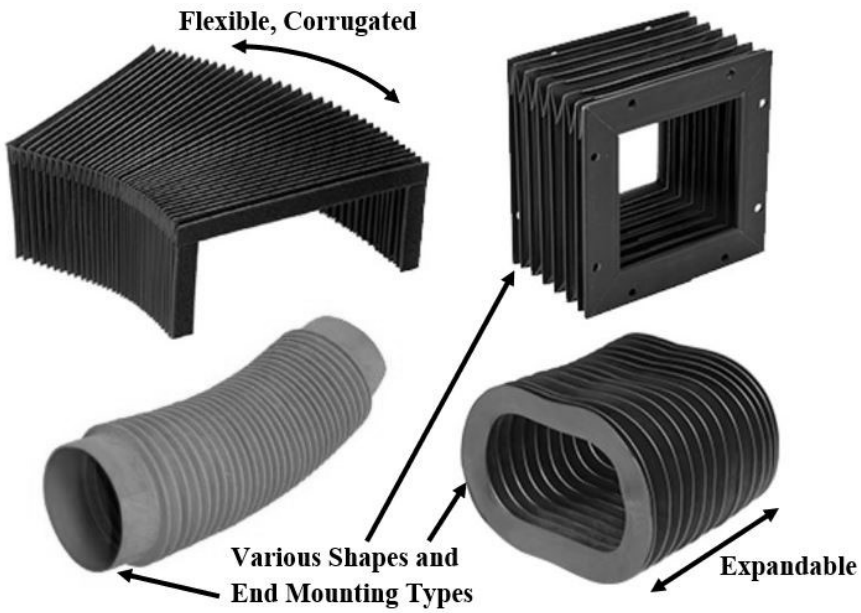

Figure 49: Various bellow cover types and shapes [68]

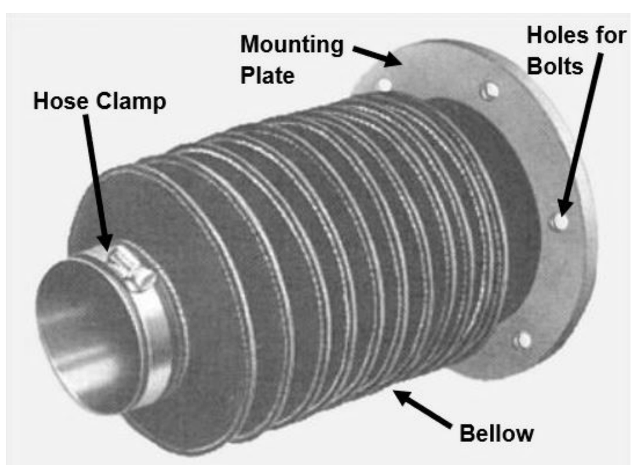

Figure 50: Mounting options for bellow cover [67]

2.5.2 Bearings

Stanford Doggo's knee joints uses two TRB rubber seal ball bearings and a steel shoulder bolt for rotation; this configuration works for them since the legs do not have abduction/adduction movement, resulting in zero axial stress on the bearings/bolt [9].

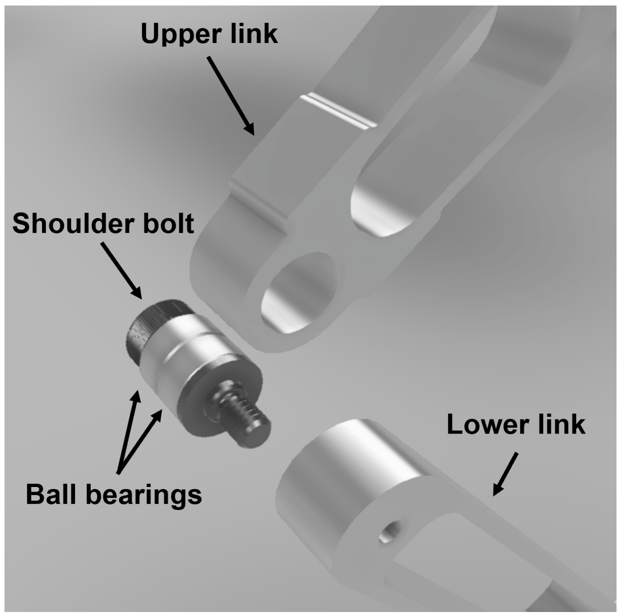

Figure 51: Stanford Doggo knee [9]

On a general point of view, bearings are used in nearly every situation where a rotary motion is produced and transferred onto a system. Bearings need to be mounted in such a way that the shaft or the bearings do not slide during the operation of the system. There are many different ways to mount and position them based on the specific design. First, a bearing can either be mounted onto the shaft or inside the housing [69]. Figure 52 presents a common method of mounting a bearing on the shaft that consists of holding the bearing against the shaft shoulder and then securing it with a component such as a lock ring, a retaining ring, or a spacer.

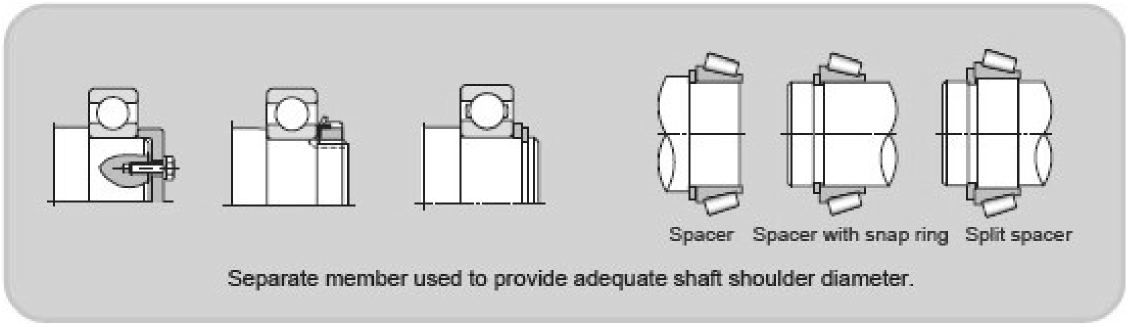

Figure 52: Bearing inner ring mounting options [69]

The other option is to mount the outer ring of the bearing inside the housing using an end cap, an inner retaining ring, or a spacer as illustrated on Figure 53.

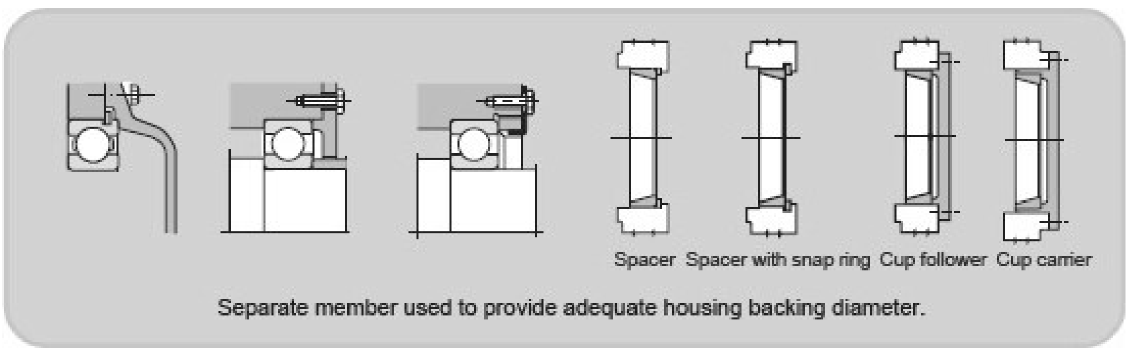

Figure 53: Bearing outer ring mounting options [69]

Combining both mounting options may be necessary based on the direction and magnitude of the axial forces. A common bearing mounting arrangement known as "fixed-floating" presented on Figure 54 can be used to axially locate the shaft [70]. This arrangement offers multiple options for the mounting devices of both the inner and outer races of the bearing. In this case, the left bearing is the only one that can take an axial load. Another bearing mounting arrangement known as "fixed-fixed", shown on Figure 55, eliminates the use of mounting devices on the shaft which may create unwanted stress concentration points [70]. This arrangement allows a single bearing to take the axial load from one direction. However, if the distance between the bearings is significant and the shaft elongates due to a rise in temperature, the bearings may fail due to the axial load in both directions created by the heat expansion of the shaft [70]. This is why the fixed-floating arrangement from Figure 54 is preferred in cases where high temperatures of operation are inevitable.

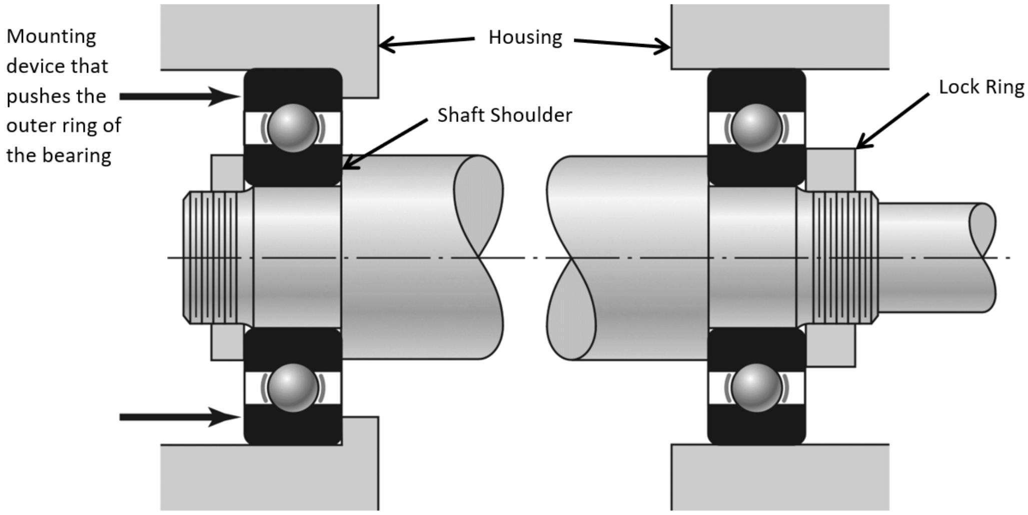

Figure 54: Bearing fixed-floating mounting arrangement [70]

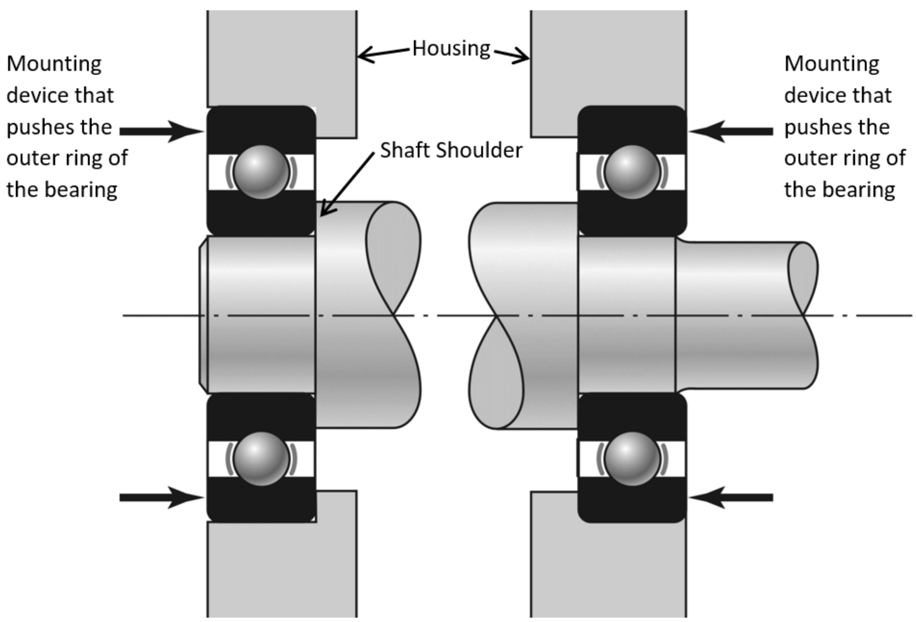

Figure 55: Bearing fixed-fixed mounting arrangement [70]

If axial loads are significant, angular contact ball bearings or tapered roller bearings can be used instead of radial contact ball and roller bearings. When mounting such types of bearings, the direction of the axial load and the preloading method must be taken into considerations [70]. Multiple options of mounting angular contact bearings are presented in Figure A.2 in Appendix A.

2.5.3 Electronics

All electronics shown in this section, with the exception of the MaxBotix MB7052 compact-housing, mount using basic metric screws and standoffs, as shown in Figure 58.

2.5.3.1 Sensors

The mandated robot must be self-sufficient; it must navigate the environment, avoid obstacles and identify trash without a human controlling it. To do so, a set of sensors must be employed. Common sensors used for robot navigation and balancing include GPS and IMUs, while sensors for obstacle avoidance include ultrasonic and laser proximity sensors [71].

In the former category, GPS units sit on the robot and use satellites to identify the position of the robot. Garmin offers a series of GPS units that are small and compact; the GPS 15x unit is 23.88 X 42.93 X 7.84 mm, weighs 7.37 g, mounts with 2 M2 screws, and consumes max 0.2625 W [72]. IMUs, or inertial measurement units, use gyroscopes and accelerometers to measure acceleration and rotation [73]. This allows the robot to identify its orientation (such as determining whether it is on an incline, at risk of flipping over, etc.). Inertial Sense offers compact all-in-one GPS/IMUs [74]. Their rugged μIMU costs $800, is 16.5 X 12.6 X 4.6 mm, weighs 1.3 g and consumes 0.625 W. Figure 56 shows this GPS/IMU model, its relative size and mounting capabilities. Individual IMUs can be purchased, such as the commonly used and inexpensive MPU-9250 [75]. It costs $14.95, is 3 X 3 X 1 mm and consumes little to no power, as it feeds of that of an Arduino or equivalent board (and thus its power consumption is considered part of the microcontroller/computers).

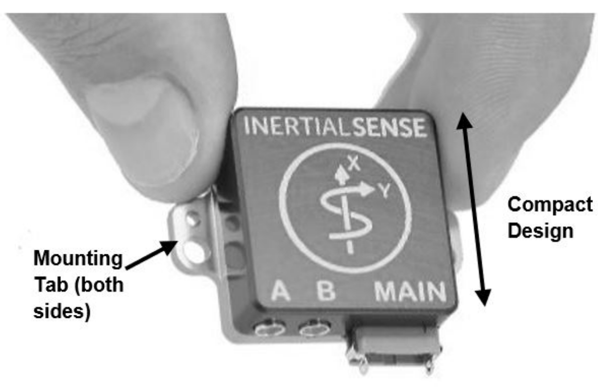

Figure 56: Combination IMU/GPS by Inertial Sense [74]

Laser or LiDAR sensors offer a greater range than ultrasonic sensors, but their performance degrades severely if the lens is wet, whereas ultrasonic sensors can operate underwater with appropriate software tweaks [71] [76]. MaxBotix offers a suite of ultrasonic sensors suitable for waterfront environments. Their MB7052 sensors are IP68 rated and have excellent corrosion resistance, as well as ranges between a few centimeters and 8 meters [77]. The ultra-compact package type costs $202.87, measures 30.48 X 35.56 X 25.27 mm, weighs 15.1 g and mounts with 4 M3 screws. The compact housing package type also costs $202.87, measures 34.7 X 34.7 X 38 mm, weighs 32 g and screws into a housing using a 3/4"-14 NPS. The package types and mounting capabilities are shown in Figure 57 . Garmin offers LiDAR (Light Detection and Ranging) sensors. Their v3HP model is IPx7 compliant and offers up to 60m range [76]. It costs $150, measures 48 X 40 X 20 mm, weighs 22 g, mounts using 4 screws and consumes 0.425 W.

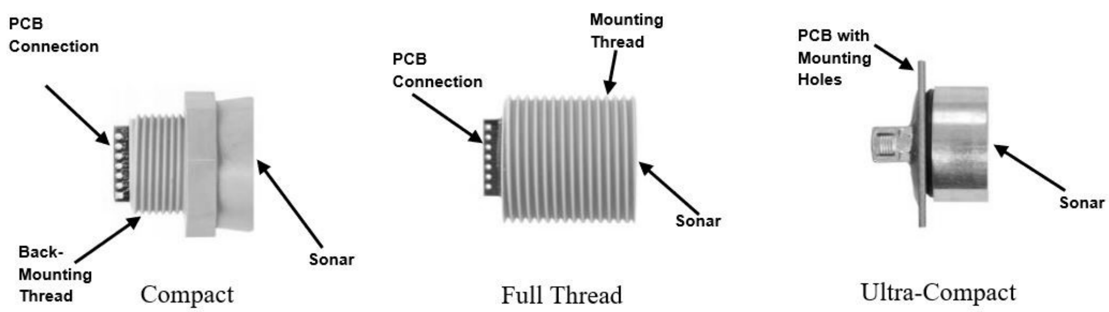

Figure 57: MaxBotix Ultrasonic Sensors Various Package Types [77]

2.5.3.2 Computing

Robots rely on microcontrollers and full computers to compute path planning, image recognition, computer vision, and SLAM, amongst a host of other tasks. Choosing the correct computer for a given application is important and can greatly impact the effectiveness of the robot. There are a few popular computers on the market for robotics applications.

Arduino is a microcontroller designed for makers [78]. Built for simple tasks and instructions, it features a 16 Mhz processor and 0.232 W power draw at 5 V and 46 mA [79]. It costs $22, measures 68.6 X 53.4 mm, weighs 25 g and is mounted with 4 M3 screws [80]. It's schematics are similar to those shown in Figure 58.

Raspberry Pi is a single-board computer, whose 4th generation was released this year [81]. They have been used in a plethora of robots, including the Hexapod v2 [13]. Running at 5 V and requiring a 3 A power supply, the Raspberry Pi 4 pulls 1 A, or 5 W [82]. It

Table 1: Comparison of compute units

Name	Weight (g)	Power (W)	Performance
Arduino Uno R3	25	0.232	Low
Raspberry Pi 4	46	5	Medium
Jetson TX2	88	7.5	High

costs $55, measures 88 X 58 X 19.5 mm, weighs 46 g and is mounted with 4 M2.5 screws [83] [81]. Although offering more than double the performance of the previous generation of Raspberry Pi, its lack of a dedicated GPU unit reduces its usefulness for computer vision applications [84].

The NVIDIA Jetson TX2, shown in Figure 58, is a machine learning oriented single-board computer with dedicated GPU for accelerated machine learning and computer vision tasks [85]. It offers nearly double the performance of the Raspberry Pi 4 for general compute tasks and likely 6 or more times the performance for computer vision applications, while consuming 7.5 W of power at 9-12 V [84] [86] [87] [88]. It costs $479, measures 87 X 59 X 10 mm, weighs 88 g and is mounting with 4 M3 screws [89].

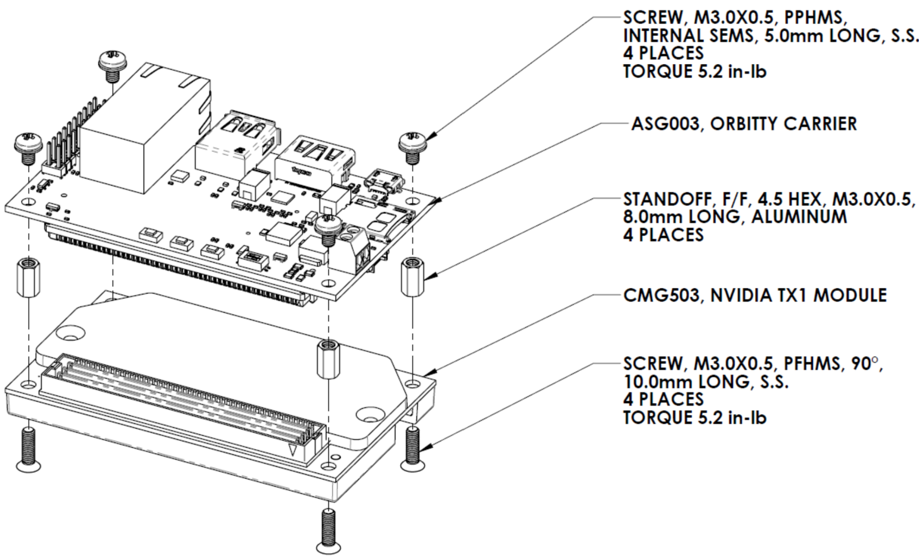

Figure 58: Mounting diagram for NVIDIA Jetson TX2 to auxiliary board (similar mounting method is used in all other discussed electronics) [90]

A comparative table of all 3 computer options is shown in Table 1.

2.5.3.3 Motor Controllers

Motor controllers are often closed-source and are purchased specifically to be used with a certain motor. There are also open source drivers that are designed to be compatible with a wide range of motors.

ODrive is a commonly used open-source motor driver [41]. Figure 59 illustrates the four oDrives used on the Stanford Doggo to actuate the 8 onboard DC motors [9]. Each unit can run at 24-48 V, provide over 100 A peak power per motor, and is designed to power 2 motors, giving a total power draw maximum of 480 W per motor, or 960 W per drive unit [41]. The drives are 135 X 50 mm and cost $159.

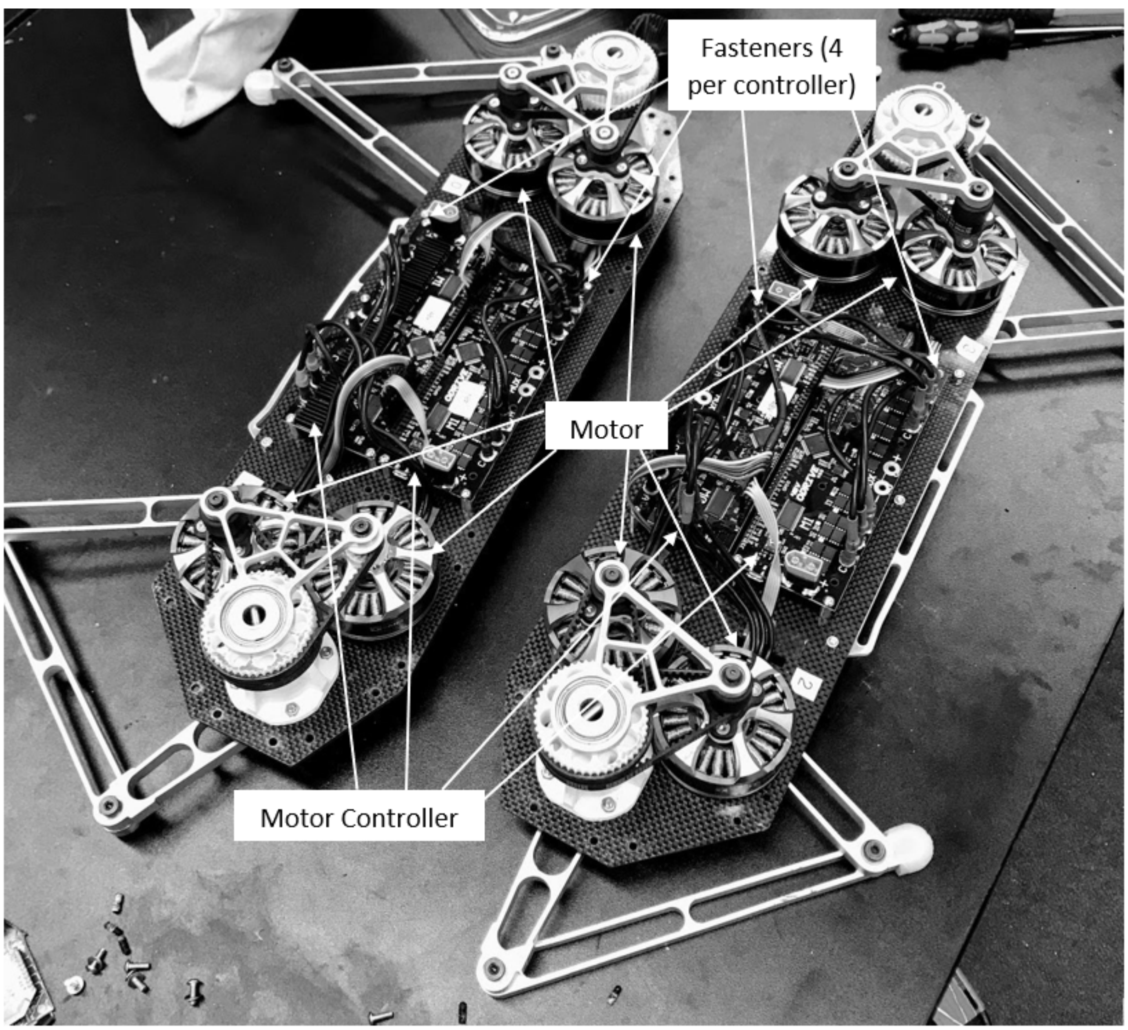

Figure 59: Layout of oDrive motor controller of the Stanford Doggo [9]

2.5.3.4 Battery Pack

While the robot may have a solar panel to provide power, the sun is not always out, meaning an auxiliary power source is necessary to run while cloudy or during the night, likely in the form of a battery power pack. Tesla batteries are composed of 18650 cells; the 85 kWh pack contains 16 modules of 444 cells for a total of 7104 cells [91]. These have a nominal voltage of 3.7 V and capacities and discharge rates varying between 2000-3500 mAh and 5-40 A respectively [92]. The Panasonic NCR18650B cells used by Tesla cost $4.99, have a 3400 mAh capacity and 4.9 A discharge rate. All 18650 cells are 18.63 X 65.08 mm and weigh approximately 47.5 g [92]. They can be combined together to create higher voltage, current or capacity batteries [93]. In this case, they require a Battery Management System to avoid overcharging and balance cell charging and discharging when in a battery [94] [95]. Figure 60 shows a purchasable 18650 battery pack from Cult3D.

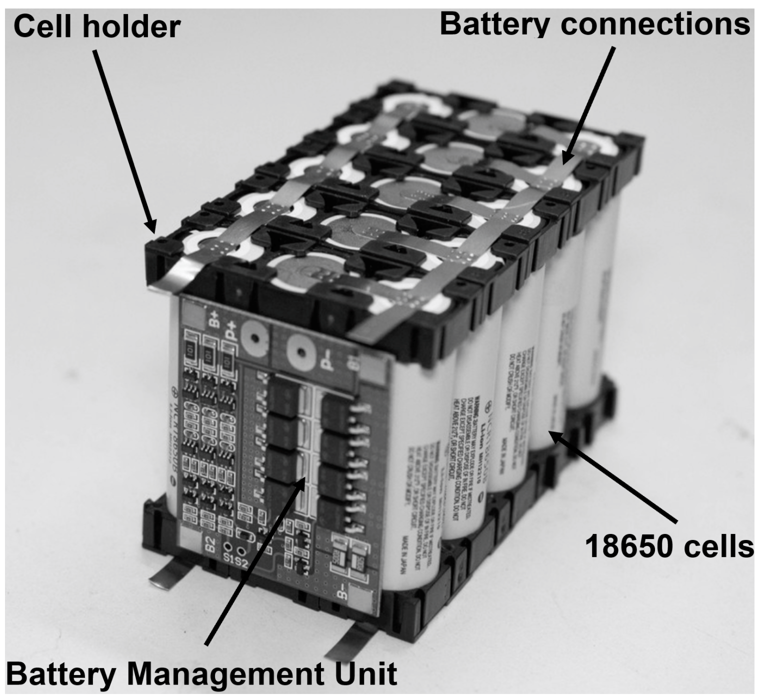

Figure 60: 18650 battery pack [96]

Battery Management systems can be purchased of the shelf for arrays of 18650 cells; OrionBMS for example offers BMS' for 24 to 168 cells in 12 cell increments, can input 8 to 30 V, consumes less than 2W and cost between $820 and $1680 [97]. Their 24-72 cell version measures 164.9 X 158.8 X 72.6 mm and weighs 1134g. It is mounted using 6 M2.5 screws in THRU holes.

2.5.3.5 Electronics Table

Table 2 outlines the specifications of the required electronic components, for some selected options.

Table 2: Electronics List

Role	Name	Cost ($)	Power Consumption (W)	Weight (g)	Dimensions (mm)
Computer	Arduino Uno [78]	22	0.232	25	69x53x?
Computer	Raspberry Pi 4 [81]	55	5	46	88x58x20
Computer	Jetson TX2 [85]	479	7.5	88	87x59x10
GPS	Garmin GPS 15x [72]	44	0.263	7.4	24x43x8
GPS/IMU	Inertial Sense μIMU [74]	800	0.63	1.3	17x13x5
IMU	MPU-9250 [75]	15	N/A	N/A	3x3x1
Ultrasonic	MaxBotix MB7052 [77]	203	N/A	15	35x30x25
LiDAR	Garmin LiDAR-Lite v3HP [76]	150	0.425	22	48x40x20
Driver	oDrive [41]	159	N/A	N/A	135x50x?
BMS	OrionBMS 24 cell [97]	$820	2	1134	165x159x73

2.5.3.6 Encoders

Encoders are sensors that measure the shaft angle of rotation. These signals are used to precisely control the positioning of servo motors by analysing feedback signals and adjusting the servo motor rotation accordingly. [98]

Rotary encoders such as the 1024 P/R (quadrature) produced by Karlsson Robotics, as shown in Figure 61, are coupled at the shaft extremity. A shaft coupling as shown in Figure 62 is required to mount the encoder in the Figure 61. Note the encoder must also be mounted on a bracket not rotating with the connected shaft.

Figure 61: Encoder sensor with shaft [99]

Figure 62: Flexible Coupling [100]

2.5.3.7 Cable Feed Through

Any electrical wire connecting to exterior components, such as motors on leg joints, must be hermetically sealed and waterproof. Special seals, such as cable feed through must be used to seal the wires entry points as shown in Figure 63.

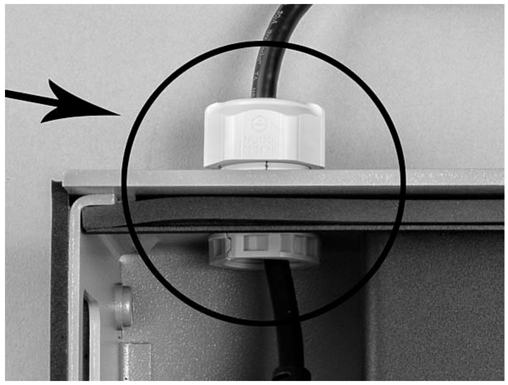

Figure 63: Cable feed through example [101]

Feed through seals can pass one or multiple wire; the connection can be parallel or perpendicular as shown in Figure 64 , Figure 65 and Figure 66.

Figure 64: Parallel one wire feed through [102]

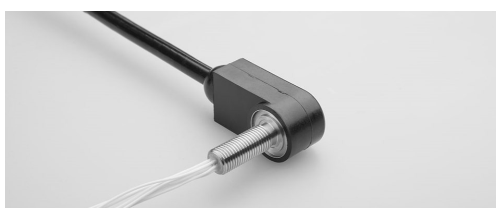

Figure 65: Perpendicular multiple wire feed through [102]

Figure 66: Parallel multiple wire feed through [103]

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A Appendices

A.1 Standards

Table A.1: List of possible Standards and Regulations

Organization	Standard Number	Standard Name	Description
ASTM	E2991 / E2991M - 17	Evaluating Response Robot Mobility: Traverse Gravel Terrain.	Test method to determine capability of robot in gravel terrain [104].
ASTM	E2992 / E2992M - 17	Evaluating Response Robot Mobility: Traverse Sand Terrain.	Test method to determine capability of robot in sand terrain [105].
ISO	15066:2016	Robots and robotic devices	Specifies collaborative robot safety requirements [1].
ISO	10218-1:2011	Safety Requirements for industrial robots. Part 1: Robots	Specifies requirements and guidelines for the inherent safe design, protective measures and information for use of industrial robots [106].
ISO	13482:2014	Safety requirements for personal care robots	Provides requirements to eliminate, or reduce, the risks associated with these hazards [107].
ISO	18646-2:2019	Performance criteria and related test methods for service robots – Part 2: Navigation	Test method to determine mobility service of robot [108].
ISO	13849-1:2015	Safety-related parts of control systems – Part 1: General principles for design	Safety requirements for the design and integration of safety related parts [109].
ISO	13850:2015	Emergency stop function	Requirement and principle for the design of emergency stop function [110].

ISO	13854:2017	Minimum gaps to avoid crushing of parts of the human body	Avoiding hazards in crushing zones [111].
ISO	13855:2010	Positioning of safe-guards with respect to the approach speeds of parts of the human body	Parameter specification for approach speed of parts of the human body [112].
ISO	14118:2017	Prevention of unexpected start-up	Requirements in the design to prevent unexpected machine start up [113].
ISO	13857:2008	Safety distances to prevent hazard zones being reached by upper and lower limbs	Establishes safety distances from hazard zones [114].
RIA	R15.06-2012	Industrial Robots and Robot Systems-Safety Requirements	Safety requirements for the design and use of [115].
RIA	TR15.606-2016	Collaborative Robots	Safety requirements specific to collaborative robots [116].
Canada	N/A	Hazardous Products Act	Compliance to all regulations set by Health Canada [117].
Canada	N/A	Consumer Product Safety Act	Compliance set by Health Canada [118]
IEC	60529	Ingress Protection Marking	Capacity of an electronic device to protect against the intrusion of solid objects, dust and water [20].

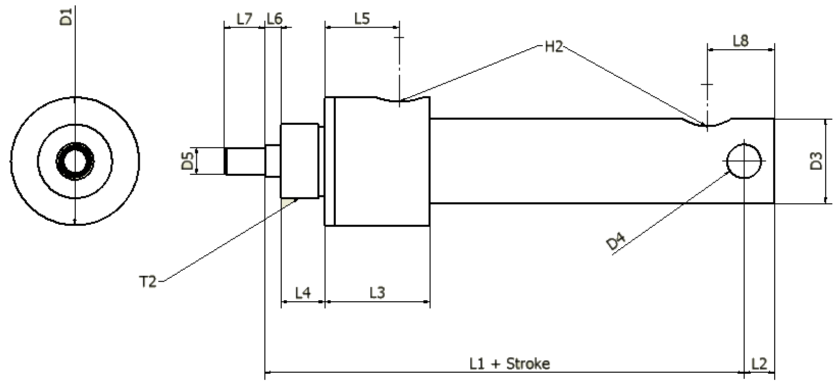
A.2 MiniHyQ

Linear hydraulic actuators are no longer available from Fluitronics; the spec sheet for the Hydro-Lek HLK 14000 is below. This is an alternative actuator provided by Khan in his analysis [6] with similar operating pressure and dimensions.

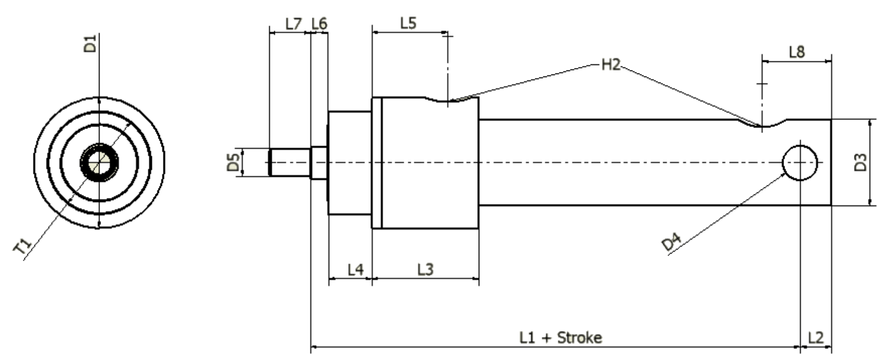
HLK 14000 Series **Industry Standard Cylinders**

- Highly versatile, hard anodised aluminium cylinders
- Lightweight and highly corrosion resistant
- Range of mounting adaptors
- Interchangeable with industry standard components
- Alternative hydraulic connection adaptors available
- Available in 10mm, 16mm, 20mm & 25mm bore diameters

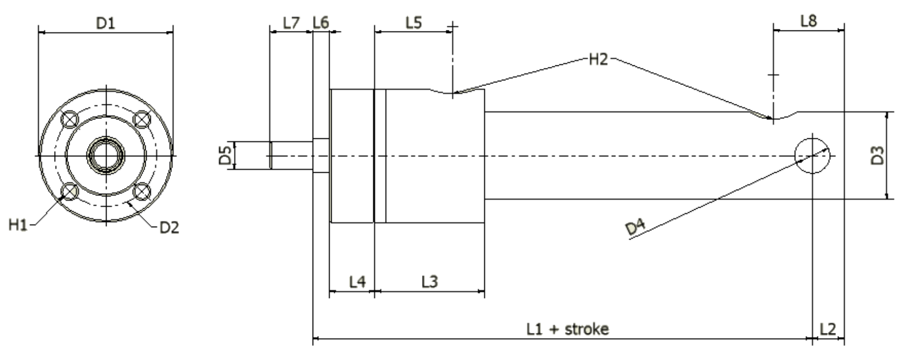
Rear Eye Mount



Nose thread Mount



Rear Eye Mount



Cylinder	Rod	Bore	D1	D2	D3	D4	D5	L1	L2	L3	L4	L5	L6	L7	L8	H1	H2	T1	T2
14 – 10	6	10	32	24	20	5	M5x0.8	68	6	30	10	20	6	8	16	M4x0.7	M8x1.0	M22x1.5	M18x1.0
14 – 16	9.5	16	38	29	25	8	M8x1.25	85	8	31	13	21	8	12	20	M5x0.8	M8x1.0	M30x1.5	M22x2.5
14 – 20	12.7	20	44	34	32	10	M10 x1.5	97	9	38	16	26	10	18	22	M6x1.0	M8x1.0	M36x2.0	M24x2.0
14 – 25	15.9	25	50	40	38	12	M12x1.75	107	12	40	20	26	13	22	25	M6x1.0	M8x1.0	M42x2.0	M30x2.0

(All measurements in millimetres)

Specification:

Cylinder Construction	ISO6082 Hard Anodised Aluminium
Piston rod	316 Stainless Steel
Working Pressure	210 bar max
Temperature range	-40°C to +80°C
Face/Nose Mount Adapters	316 Stainless Steel
Hydraulic Ports	M8 x 1.0 pitch to suit Hydro-Lek banjo fittings or 1/8 NPT adapter

A.3 Custom Gasket Materials from Protocase Manufacturer

As an example of possible gasket materials and applications, the available materials from Protocase are shown below [64].

Stocked Gasket Materials

Material	Thickness	Part Number
Adhesive Backed High-Strength Multipurpose Neoprene Rubber Durometer 50A (36" Wide)	1/16"	8456K31 50A
Adhesive Backed High-Strength Multipurpose Neoprene Rubber Durometer 70A (36" Wide)	1/16"	8456K31 70A
Oil-Resistant Neoprene/Vinyl/Buna-N Foam, Extra Soft (54" Wide)	1/8"	85175K17
Oil-Resistant Neoprene/Vinyl/Buna-N Foam, Extra Soft (54" Wide)	3/16"	85175K23
High-Strength Multipurpose Neoprene Rubber Durometer 40A (36" Wide)	1/16"	8568K381 40A
High-Strength Multipurpose Neoprene Rubber Durometer 60A (36" Wide)	1/16"	8568K381 60A
Weather-Resistant Neoprene Foam, Adhesive Backed, Soft (36" x 48")	1/8"	8613K31
Wear-Resistant Quick-Recovery Polyurethane Foam, Adhesive-Back Sheet, Medium (36" x 54")	1/16"	86375K66
Abrasion-Resistant SBR Rubber, Red Durometer 75A (36" Wide)	1/16"	9454K2
Multipurpose Oil-Resistant Gasket Material, Aramid/Buna-N Sheet Automotive Style (60" x30")	1/32"	9470K48
Multipurpose Oil-Resistant Gasket Material, Aramid/Buna-N Sheet Automotive Style (60" x30")	1/16"	9470K49

Non-Stock Requests

Need a gasket made from material we don't currently stock? We are happy to source additional non-stocked materials for additional lead time and cost.

- Fibre Gasket
- Rubberized Cork
- Styrene Butadiene Rubber
- And many more

Figure A.1: Custom gasket materials from Protocase [64]

A.4 Angular Contact Bearings Arrangement

Based on the magnitude and direction of the radial and thrust loads, multiple arrangements combining sets of bearings are possible and presented in Figure A.2.

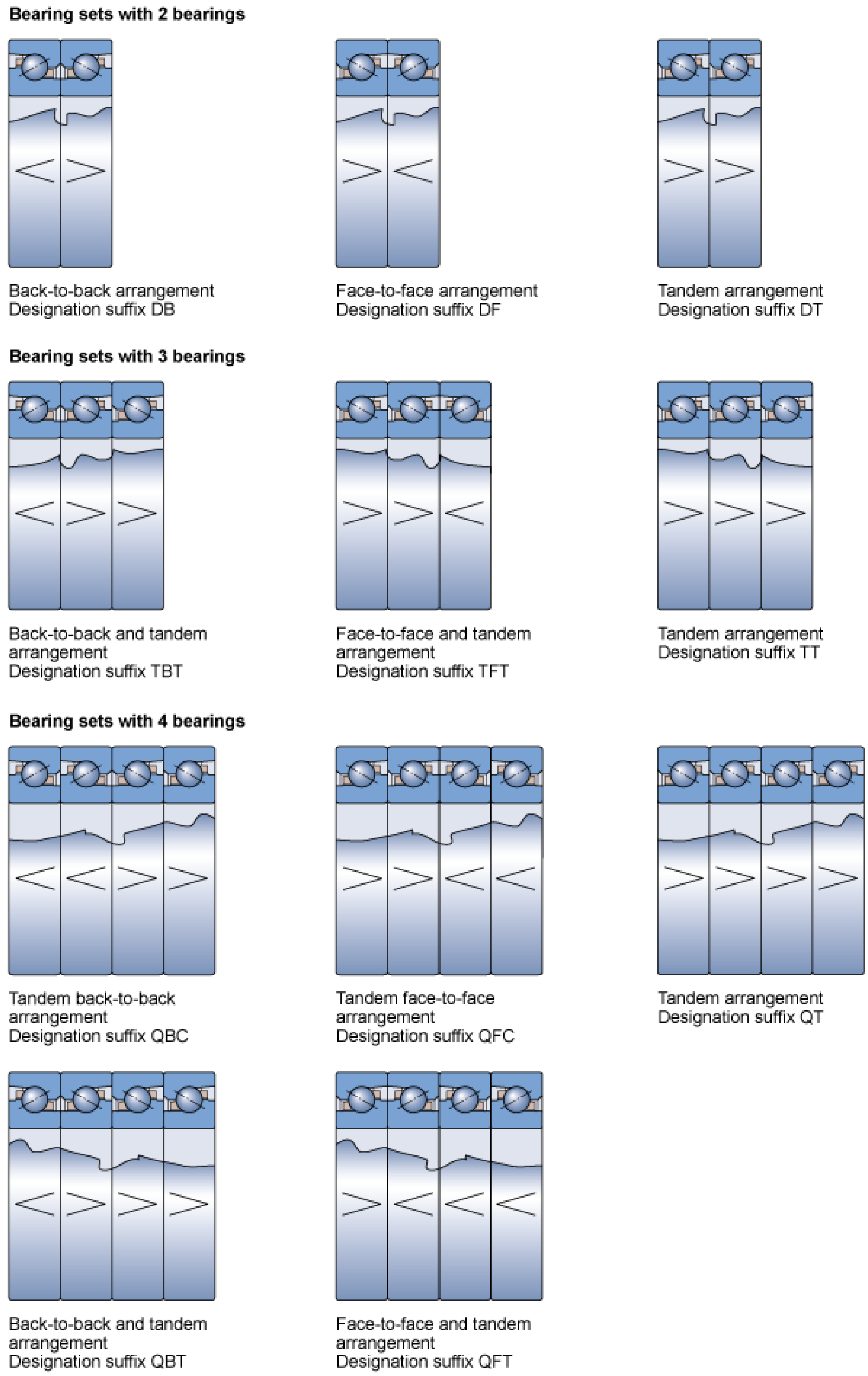


Figure A.2: Multiple examples of back-to-back, face-to-face, and tandem arrangements for different sets of angular contact ball bearings [119]

A.5 Materials and Coatings

As an outdoor application, corrosion free and weather proof materials are required. Aluminum, Stainless Steels, Galvanized Steel and Red Metals (Copper, Brass and Bronze)[120][121][122].

As **Aluminum** contain almost no iron in its composition, it cannot rust. In addition, when exposed to water, the aluminum will create an aluminum oxide layer creating an additional rust barrier and protecting the metal underneath. Aluminum is found in aircraft, cars and bicycles. Aluminum will corrode easily when exposed to salt [120][121][122].

Galvanized steel is also durable against rust. It is the zinc protective coat on the steel that protects the steel from rusting. In extreme environments, the zinc layer will be rendered ineffective in such causing the steel to rust. Water and condensation can oxidize the zinc coating, called white rust. Galvanized steel is specially used do to its affordable price [120][121][122].

Other metals containing almost no iron and are considered highly durable and resistant are the Red Metals, which includes **Copper, Bronze and Brass**. However, red metals do oxide forming a green layer protecting the metal from further oxidation [120][121][122].

Stainless steel is another great outdoor weather proof material due to its durability and inability to rust. The most common grades for outside use includes 304 and 316 due to its high composition of nickel and chromium [120][121][122].

Plastics can also be great materials for outdoor use. The best plastics for outdoor use includes Acrylic, Polycarbonate, HDPE [123][124].

Acrylic has high weather resistance, work in temperature ranging from -40 to 180 degree Fahrenheit, and is UV stabilized [123][124].

Another UV stabilized plastic is **Polycarbonate**, with work temperature from -40 to 240 degree Fahrenheit and excellent with high impact resistance [123][124].

Polyethylene HDPE has high abrasion and corrosion resistance properties with a reasonable impact strength and operates under 32 to 210 degrees Fahrenheit.However, the plastic is not UV stabilized and less resistant to sun rays [123][124].

As an alternative to waterproof and corrosion resistant material for the design which can have additional cost over other cheaper steels and metals, rust coating and anti corrosion coating can provide waterproof and chemical proof properties, protect against organism such fungi, algae and moss, and resist harsh environments including acid rain and salt water.

To properly coat a metal, multiple layers of coating must be applied. In order of operations: Primer, Sealer, Intermediate Coat, and Finishing Coat. All layers and specifically the intermediate coat will also depend on the degree of corrosivity exposed to the metal [125].

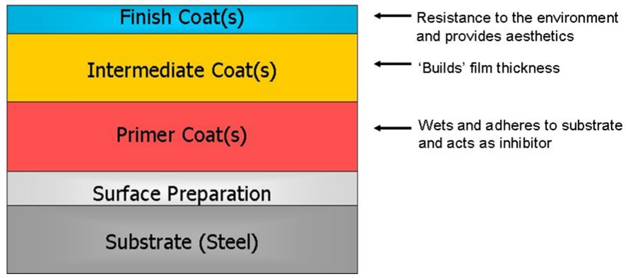


Figure A.3: Typical paint system diagram [126]

A.6 Physical Seal of Enclosure Using Welding

It is possible to weld the chassis to provide a physical seal against the elements. This option is a permanent seal, thus the previous solutions shown in the static seals section may still be needed for easily-removable maintenance points. One potential process is seam welding which consists of passing two overlapped sheet metal parts between two wheel-shaped electrodes. The current then goes through the parts, and their contact resistance causes them to heat up and coalesce together, as shown in figure A.4. This method is useful to weld seams in conductive materials, and is efficient at creating waterproof seals [127].

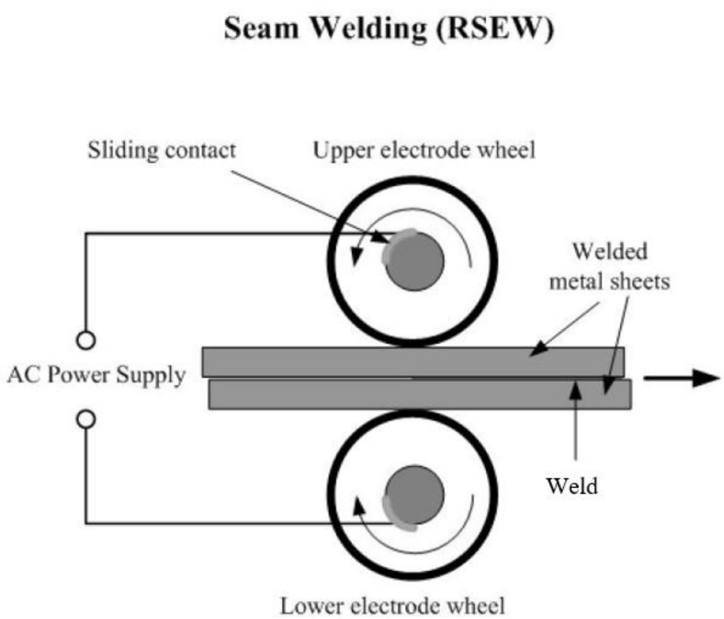


Figure A.4: Resistance Seam Welding Method [128]

Another process, which can be used with plastics, is ultrasonic welding. This process uses high frequency vibrations and pressure to create a weld,as shown in figure A.5. This process is often used in the packaging industry and can thus provide a leak-proof weld. It is also used with a wide variety of materials [127] [129].

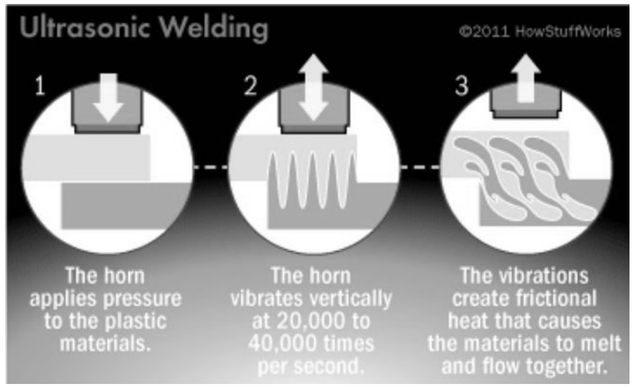


Figure A.5: Ultrasonic Welding Method [130]

A.7 Interior Dynamic Seals

Rotary shaft lip seals are available in many shapes and materials for different applications. Figure A.6 shows the mounting of a lip seal that is oriented to exclude contaminants from a bearing [131]. These seals generally have a metal shell that is press mounted to fit in a bore in the housing [132].

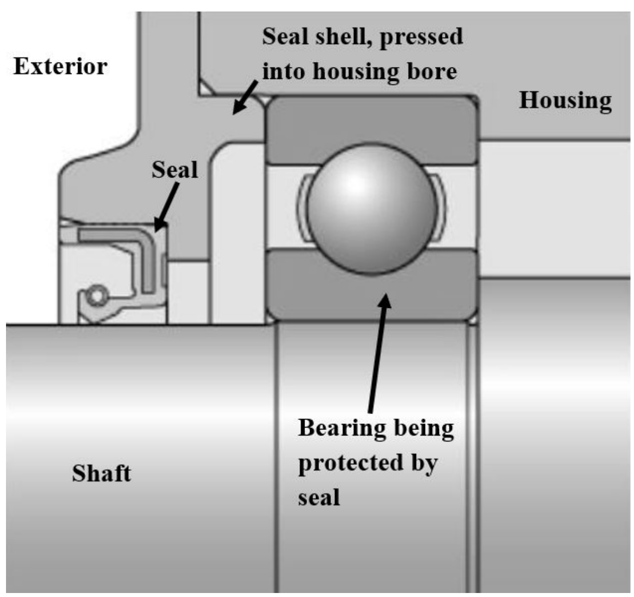


Figure A.6: Possible configuration and mounting of a rotary lip seal [131]

Similar seals, called U-Cup seals, are available for reciprocating motion applications (see figure A.7). For mounting, they are generally compressed within a groove in the housing or shaft/piston. Both these types of seals are useful to keep most particles, such as sand and dirt, out of a system, but are often meant to use in lightweight applications and may not be completely waterproof [133].

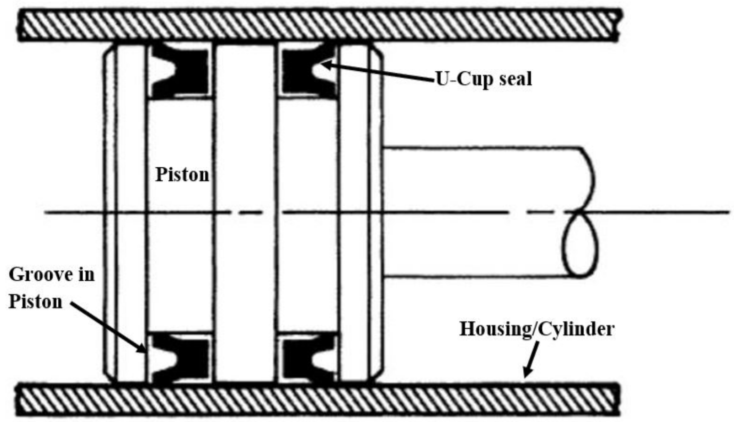


Figure A.7: U-Cup seals used on a piston [133]

To provide a waterproof seal on a rotating shaft, a mechanical seal can be used. Although they may have different configurations, they usually function by having two rings: one rotating with the shaft and the other stationary and fixed to the housing. The seal is thus provided at the shaft, at the housing and between the two rings which are in contact [63] [134]. An example of the mounting of a mechanical seal is shown in figure A.8.

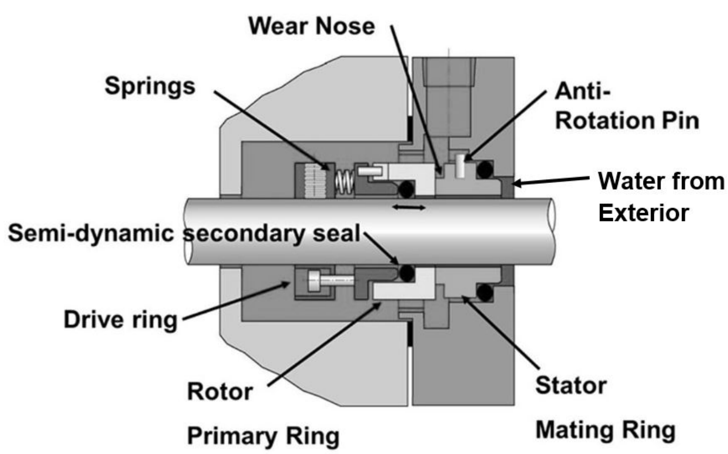


Figure A.8: Possible configuration and mounting of a mechanical seal [135]

A.8 Hydraulic

For MiniHyQ, Moog E024 servo valves were selected for actuation control, while a TAKAKO axial piston pump, Neu motor 10kW DC motor and single stage 6.5:1 planetary gearbox manage the hydraulic circuit [59].

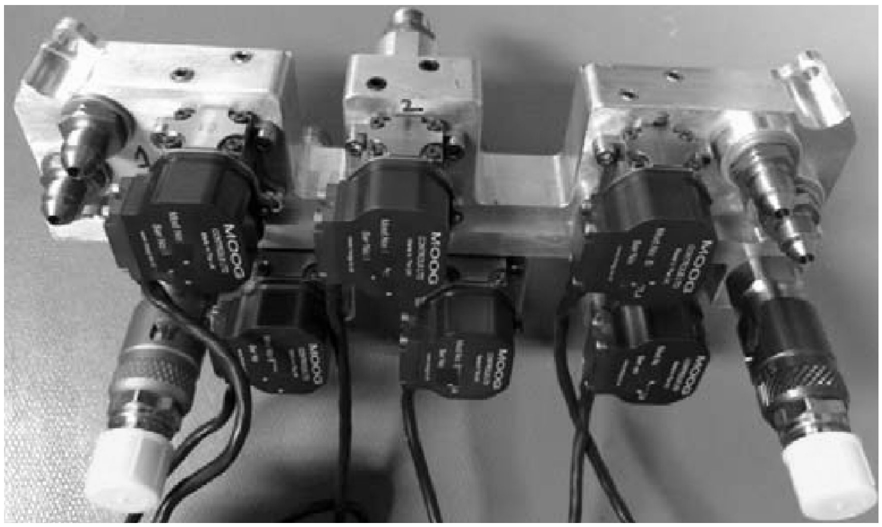


Figure A.9: Moog servo valve assembly for front or rear legs [59]

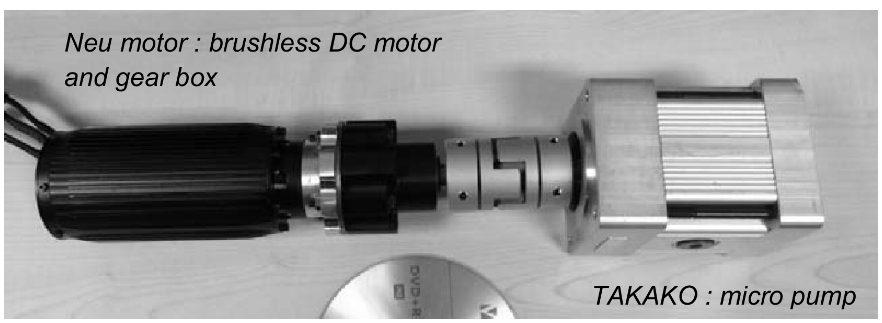


Figure A.10: MiniHyQ hydraulic Neu motor and TAKAKO pump [59]

Figure A.11 and Figure A.12 demonstrate typical components of a hydraulic system for an actuator; in both cases the actuator is linear, however the linear actuator can be replace by rotary actuator and other types of hydraulic actuator.

Typical hydraulic system includes the following component: hydraulic pump paired with a motor, directional control valve to control the pressure and the flow of the liquid (water), filter, and a reservoir for the excess liquid in the system. Pressure gauge are installed across the system to monitor the pressure in the system but are not essential to the functionality of the system, the pressure relief valve enables to control the pressure in the system by enabling the liquid to discharge from the valve when high pressure levels are reached.

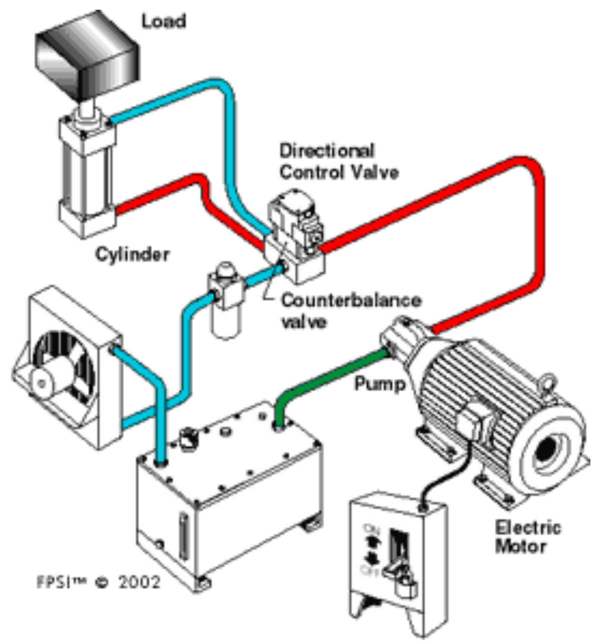


Figure A.11: Basic hydraulic system for linear activator [136]

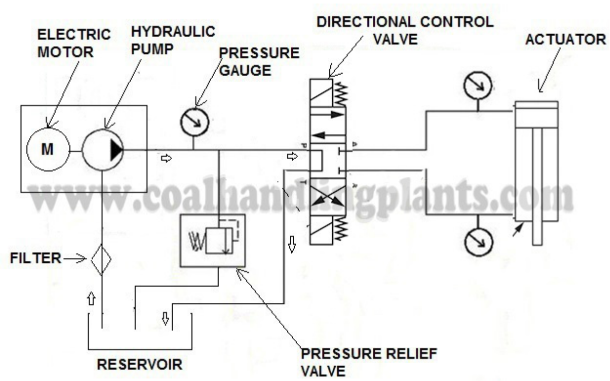


Figure A.12: Basic hydraulic system for linear activator schematic [137]

A.9 Solar Panel Specifications from Wholesale Solar

The following are the specifications from Wholesale Solar for a 100 W rigid solar panel recommended for RV's [25] and a 100W flexible solar panel recommended for RV's [27].

SOLARLAND®
Solar Technology and Solutions

SLP100-12U

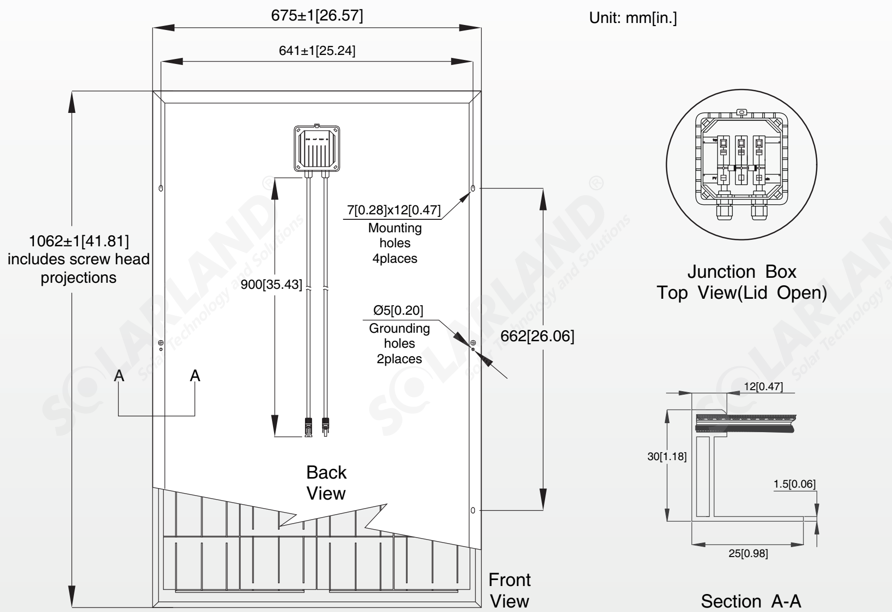
High Efficiency Multicrystalline PV Module

Electrical Characteristics	SLP100-12U
Product code	100011206C
Maximum power (Pmax)	100W
Voltage at Pmax (Vmp)	17.2V
Current at Pmax (Imp)	5.81A
Open-circuit voltage (Voc)	21.6V
Short-circuit current (Isc)	6.46A
Temperature coefficient of Voc	-(80±10)mV/°C
Temperature coefficient of Isc	(0.065±0.015)%/ °C
Temperature coefficient of power	-(0.5±0.05)%/ °C
NOCT (Air 20°C; Sun 0.8kW/m² wind 1m/s)	47±2°C
Operating temperature	-40°C to 85°C
Maximum system voltage	1000V DC
Power tolerance	± 5%

*STC: Irradiance 1000W/m², AM1.5 spectrum, module temperature 25°C
*NOCT:Nominal operating cell temperature (the data is only for reference)

Module Diagram

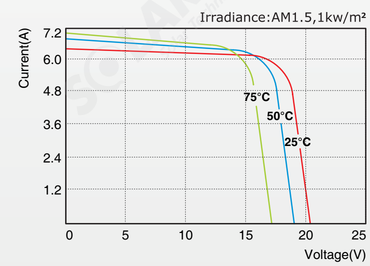
Dimensions in brackets are in inches.
Un-bracketed dimensions are in millimeters.
Unit: mm[in.]



Features

- Nominal 12V DC for standard output.
- Outstanding low-light performance.
- Heavy-duty anodized frames.
- High transparent low-iron,tempered glass.
- Rugged design to withstand high wind pressure, hail and snow load.
- Aesthetic appearance.

Characteristics



SLP100-12U I-V Curves

Specifications	SLP100-12U
Cells	Polycrystalline silicon solar cell
No. of cells and connections	36(4X9)
Module dimension	1062mm[41.81in.]x675mm[26.57in.]x30mm[1.18in.]
Weight	8.90kg[19.62lbs]
Packing information(Carton)	1100mm[43.31in.]x715mm[28.15in.]x80mm[3.15in.]/(2pcs/ctn)

*Limited warranty: 5-year limited warranty of materials and workmanship; 10-year limited warranty of 90% power output; 25-year limited warranty of 80% power output. For detail, please contact us.
*Specifications are subject to change without notice at any time.

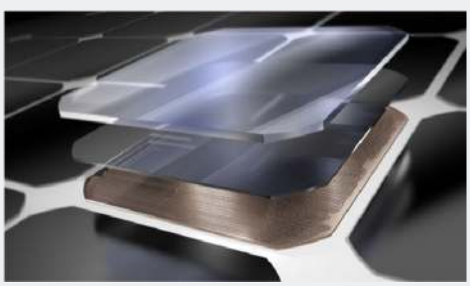
SunPower® Flexible Solar Panels | **SPR-E-Flex-110**

High Power and Flexible

Made with SunPower's highest power Gen II back contact cells, SunPower's flexible panels deliver the highest power output and the highest charging capacity in their product class. SunPower's panels are constructed with top-grade, light-weight polymer materials, allowing for easy transport, installation and panel flexing up to 30 degrees.

Designed for Toughness

The SunPower Maxeon® Solar Cell is the only cell built on a solid copper foundation. Flexible panels made with SunPower cells are resistant to power loss via cracking and corrosion, unlike conventional cells, which are much more likely to lose power when bent or subjected to a moist environment. SunPower flexible panels are the #1 choice for customers due of the combination of high power and cell ruggedness.



Maxeon® Solar Cells: Fundamentally better

Engineered for performance, designed for durability.

Easy and Low Cost Installation

The panel can be installed with adhesives and/or use of stainless steel grommets in the panel. The panels have standard quick-connect cables. An easy-to-follow installation guide is provided with each panel.

Warranty: 5 years limited power warranty of 80% of the minimum specified power rating. Designed in the USA. Assembled in France.

Typical Electrical Data at STC: 25° C, 1000 W/m² and AM 1.5		
Model	SPR-E-Flex-110	SPR-E-Flex-100
Nominal Power (Pnom)	110 W	100 W
Power Tolerance	+6/–3%	+6/–3%
Rated Voltage (Vmpp)	18.8 V	17.1 V
Rated Current (Impp)	5.9 A	5.9 A
Open-circuit voltage (Voc)	22.8 V	21.4 V
Short-curcuit current (Isc)	6.3 A	6.3 A
Power Temp Coeffiecient	–0.35%/° C	
Voltage Temp Coefficient	–58.9 mV/° C	
Current Temp Coefficient	2.6 mA/° C	
Max. System Voltage	1000 V DC IEC, 600 V DC UL	
Series Fuse Rating	15 A	

Mechanical Data	
Solar Cells	Prime monocrystalline 25% and 23% efficiency SunPower IBC cells
Junction Box	TE 1-21-2152049-1 with by-pass diode
Connectors	PV4-S (Compatible with MC4)
Cables	4 mm² (0.16 in²), 12 AWG, 450 mm (17.7 in) long
Grommets	316 Stainless Steel
Charge Controller	None provided
Weight	4.4 lb (2 kg)
Panel Dimensions	1165 x 556 x 20 mm with Jbox, 2 mm w/o Jbox (45.9 x 21.9 x 0.8 in)

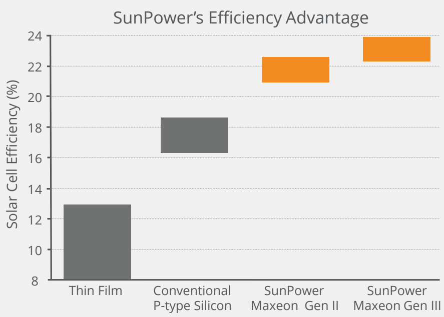
Please read the safety and installation guide.
Document # 523809 Rev F / LTR_US

A.10 Solar Cells by Sunpower [32]

MAXEON™ GEN III SOLAR CELLS

Power Advantage

SunPower designs, manufactures, and delivers high-performance solar electric technology worldwide. SunPower™ cells produce 25-35% more power compared to Conventional Cells[1] with outstanding aesthetics.



Energy Advantage

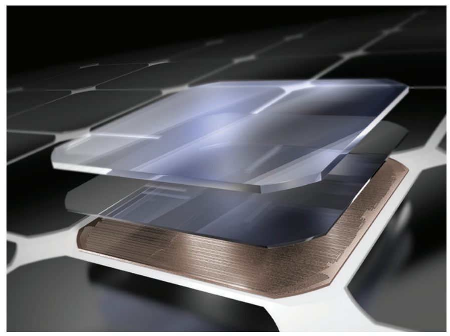
SunPower panels deliver the highest energy per rated watt compared to a Conventional Panel. (Photon International, Mar 2013, out of 151 panels tested).

- No Light-Induced Degradation = 2 - 3% more energy.
- No Temperature Coefficient = 1 - 2% more energy at 35-40°C ambient temperature.
- Low Light and Broad Spectral Response = up to 1% more energy in overcast and low-light conditions.

[1] As used throughout, "Conventional Cells" are silicon cells that have many thin metal lines on the front and 2 or 3 interconnect ribbons soldered along the front and back. "Conventional Panel" means a panel with 240W, 15% efficiency and approximately 1.6 m^2 made with Conventional Cells.

Durability Advantage

The Maxeon cell has strength and durability to survive extreme conditions year after year, enabling SunPower to provide superior, long-term performance in a broad range of applications.



- Corrosion Resistance: SunPower's tin-copper metal system is more corrosion resistant compared to the porous metal paste used in Conventional Cells, which can crack more easily and corrode.
- Crack Resistance: SunPower's cells are thinner and more flexible than Conventional Cells. When a SunPower cell does crack, the backside copper metal foundation keeps the cell intact and maintains a high power output. When Conventional Cells crack, the cell breaks apart with typically a significant loss of power.
- Eco-Friendly: SunPower cells solder to lead-free components and are RoHS compliant. Conventional Cells often require components with lead.


Photo courtesy of Hans-Peter van Velthoven


Optifuel Lab 2 Renault Trucks laboratory vehicle

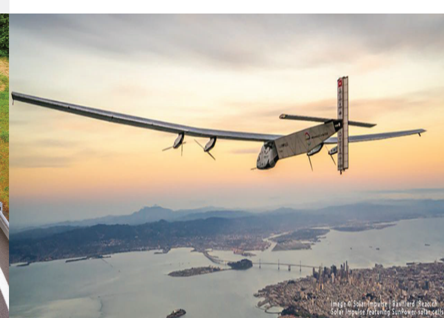


Photo courtesy of philsharpracing.com

SUNPOWER™

MAXEON™ GEN III SOLAR CELLS

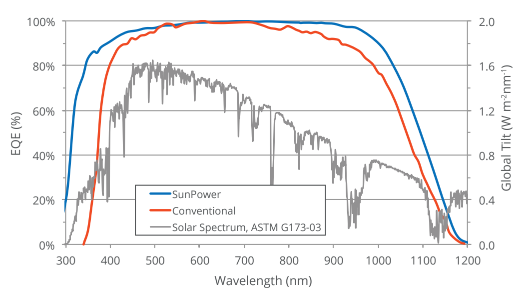
Electrical Characteristics of a typical Maxeon Gen III Cell At Standard Test Conditions (STC)

STC: 1000W/m^2, AM 1.5G and cell temp 25ºC

	Cell Bin	Pmpp (Wp)	Eff. (%)	Vmpp (V)	Impp (A)	Voc (V)	Isc (A)
Ultra Peak Performance	Me1	3.72	24.3	0.632	5.89	0.730	6.18
Ultra Premium Performance	Le1	3.62	23.7	0.621	5.84	0.721	6.15
Ultra High Performance	Ke1	3.54	23.1	0.612	5.79	0.713	6.11

Electrical parameters are nominal values.
Temp.Coefficients in SunPower Panels: Voltage: -1.74mV/ºC, Current: 2.9mA/ºC, Power: -0.29%/ºC

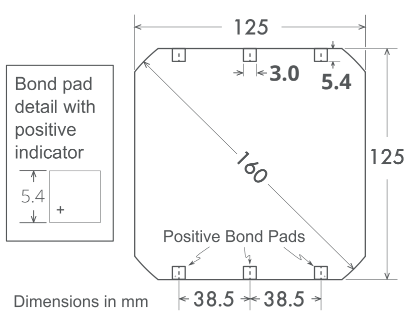
Spectral Response



References
SunPower: NREL data, commissioned by SPWR
Conventional: Progress in Photovoltaics: Research and Applications, Solar cell efficiency tables, version 36 18(5), (2010) 46–352

Cell Physical Characteristics

Wafer:	Monocrystalline silicon
Design:	All back contact
Front:	Uniform, black antireflection coating
Back:	Tin-coated, copper metal grid
Cell Area:	Approximately 153cm^2
Cell Weight:	Approximately 6.5grams
Cell Thickness:	150μm +/- 30μm

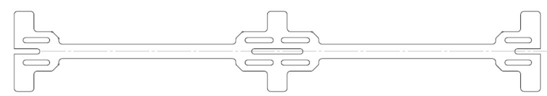


Bond pad area dimensions are 5.4mm x 3.0mm
Metal finger pitch between positive and negative fingers is 471um.
Positive/Negative pole bond pad sides have "+/-" indicators on leftmost and rightmost bond pads

Positive Electrical Grounding

If cell voltage is below frame ground the cell power output will be reduced. Therefore, modules and systems produced using these cells should be configured as "positive ground systems." If this creates a problem, please consult with SunPower.

Interconnect Tab and Process Recommendations



SunPower recommends customers use SunPower's patented tin-plated copper strain-relieved interconnect tabs, which can be purchased from SunPower. These interconnects are easily solderable and compatible with lead free processing. Tabs weigh approximately 0.3 grams.

Our patented interconnect tabs are packaged in boxes of 3600 or 36,000 each.

http://us.sunpower.com/about/sunpower-technology/patents/

Production Quality

ISO 9001:2015 certified

Soft handling procedures to reduce breakage and crack formation

100% cell performance testing and visual inspection

Packaging

Cells are packed in boxes of 1500 each; grouped in 10 shrink-wrapped stacks of 150 with interleaving. 24 boxes are packed in a water-resistant "Master Carton" containing 36,000 cells suitable for air transport.

Purchase Terms

Customers shall not reverse engineer, disassemble or analyze the Solar Cells or any prototype, process, product, or other item that embodies Confidential Information of SunPower. Customers shall not cause or allow any inspection, analysis, or characterization of any properties (whether mechanical, structural, chemical, electrical, or otherwise) of the Solar Cells, whether by itself or by a third party.

Customer agrees that it will not transfer (whether by sale, loan, gift, or other conveyance) the Solar Cells from its possession.

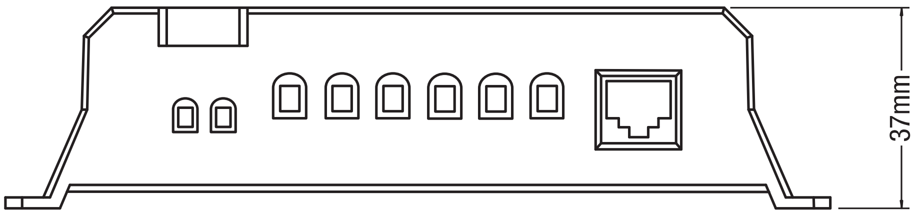
SunPower solar cells are provided "AS IS" without warranty.

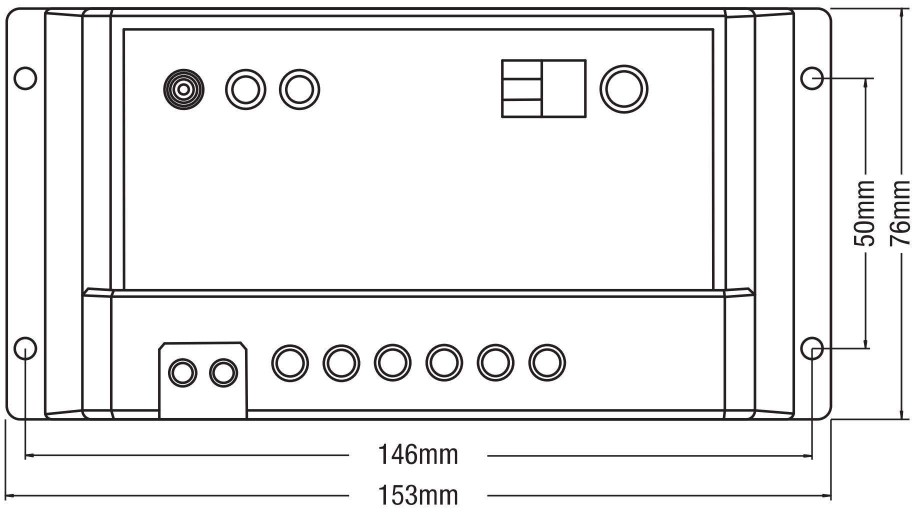
Full terms and conditions are in the Cell Purchase Agreement

A.11 Solar Regulator Specifications from REDARC Electronics [34]

SPECIFICATIONS

DIMENSIONS





GENERAL SPECIFICATIONS

System Voltage	12V			24V		
Battery Type	AGM/Gel	SLA	Calcium	AGM/Gel	SLA	Calcium
Maximum Voltage*	14.4V	14.6V	14.8V	28.8V	29.2V	29.6V
Float Voltage*	13.6V	13.6V	13.6V	27.2V	27.2V	27.2V
Maximum Input Voltage	30V			55V		
Battery Voltage Range	9 -15V			18 - 30V		
Current Limit	10A (SRP0120) / 20A (SRP0240)					
Power Rating	120W (SRP0120) / 240W (SRP0240)					
Boost Time	2 hours					
Standby Current Draw	4mA					
Nominal Current Draw	10mA					
Remote Connection	8-pin RJ-45					
Temp. Compensation	-30mV/12V/°C					
Terminals	4mm²					
Operating Temp.	-35°C to +50°C					

*Charge profile voltages will change with temperature compensation

A.12 Cooling

A.12.1 Computer Cooling

The primary cooling concern of computer cooling is the CPU, which accounts for nearly 50% of server power consumption; other elements such as memory, hard drives and voltage regulators are cooled passively or take advantage of the CPU cooling solution [138].

Air cooling is the most well established method of cooling major server components; heat sinks are attached to high flux devices while forced air convection generated by fans pulls heat away from components. They are generally mounted the same way as PC indirect liquid cooling systems as shown in figure A.15.

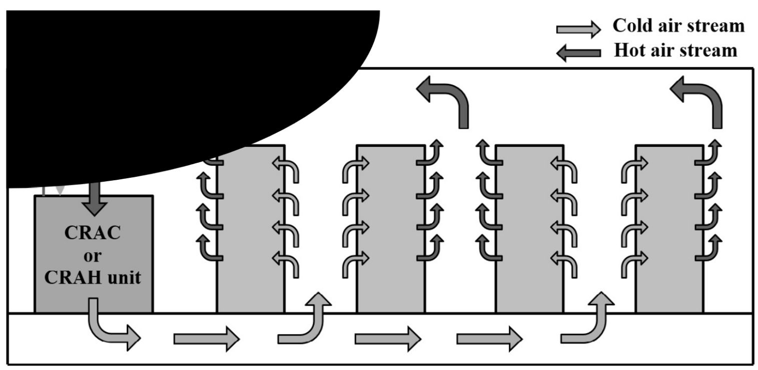


Figure A.13: Server air cooling configuration [138]. CRAC = computer room air conditioning; this unit pushes hot air outside and feeds in fresh air

Indirect liquid cooling interfaces a coolant liquid to the CPU heat-sink directly before feeding the heat outside. They allow for decreases power consumption for equivalent cooling, at the cost of higher more infrastructure to avoid leakage and proper piping.

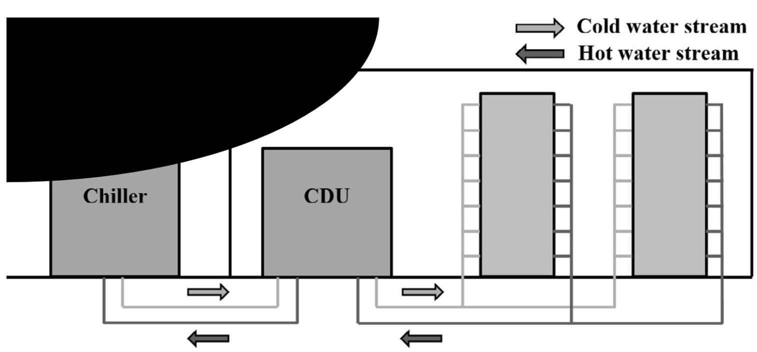


Figure A.14: Server indirect water cooling configuration [138]. CDU = coolant distribution unit

An indirect liquid cooling heat-sink for CPUs was developed by Kheirabadi and is shown below [139].

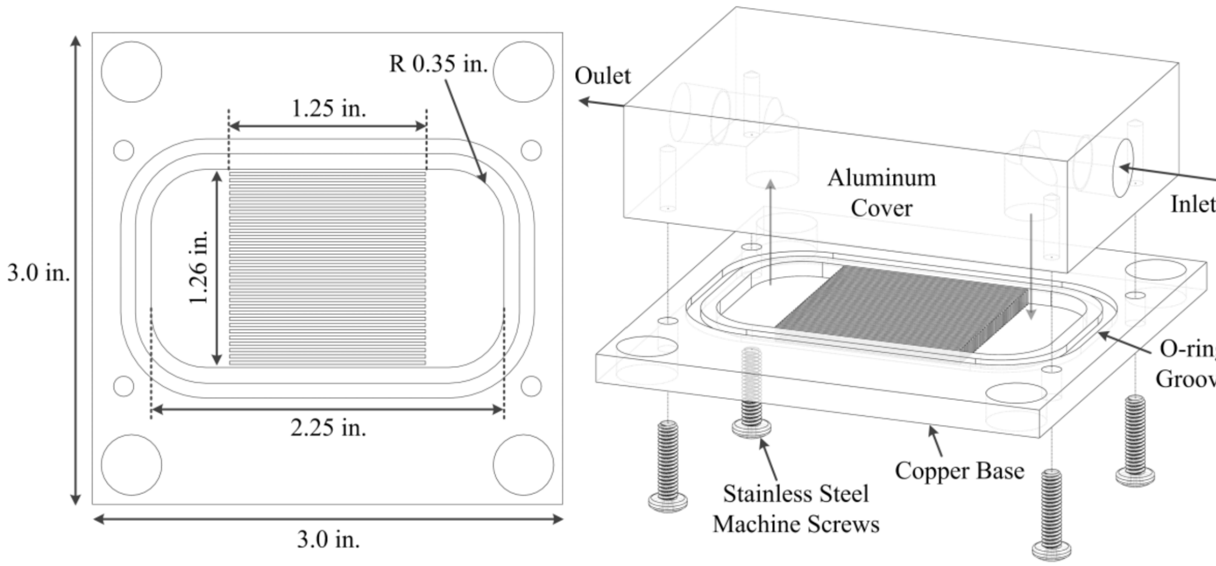


Figure A.15: Heat-sink design by Kheirabadi [139]

The corresponding heat exchanger plate is shown below (equivalent to the chiller element from figure A.14).

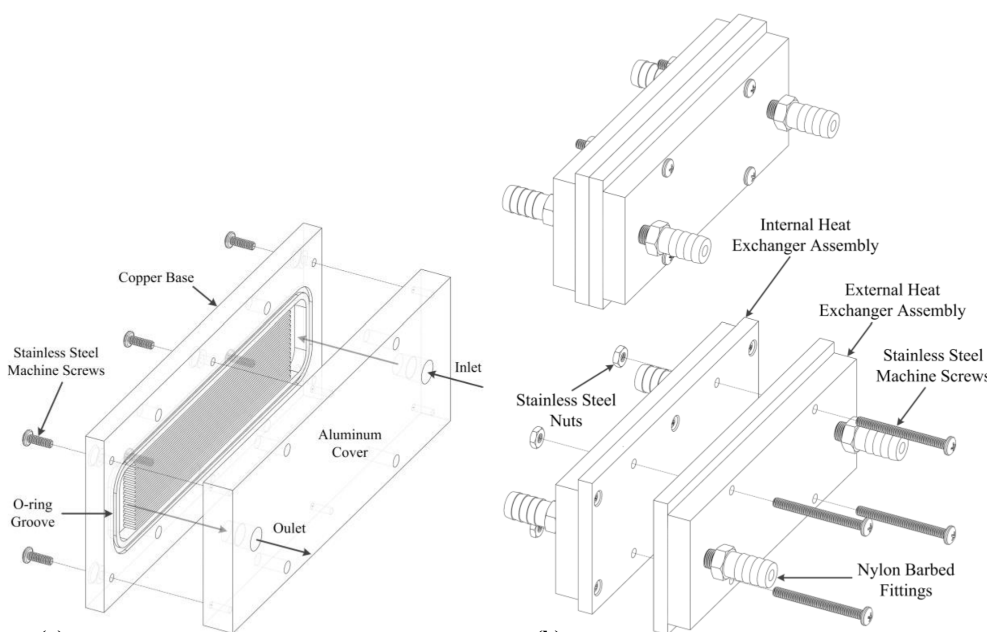


Figure A.16: Heat exchanger design by Kheirabadi [139]

Other solutions such as pool boiling and direct liquid cooling exist, however these are more esoteric.

A.12.2 Actuator Cooling

Traditionally, actuators are cooled by forcing air through their housing using an external blower motor and fan, as shown in figure below [140].

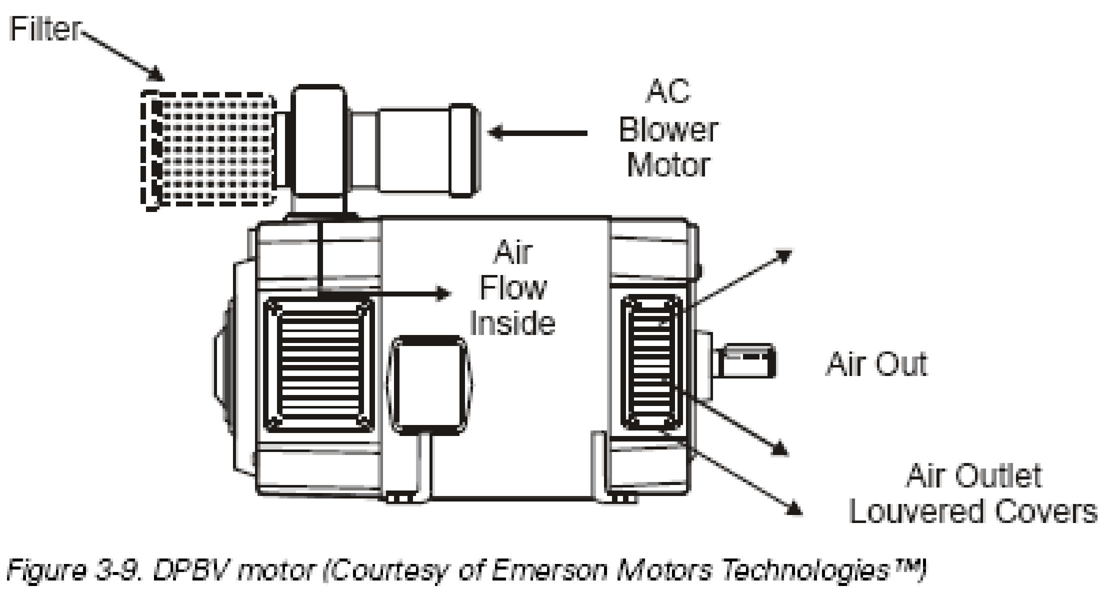


Figure A.17: Traditional DC motor cooling technique [140]

Boats with inboard motors (where the motor is not exposed to the outside) use a system of liquid coolant (typically antifreeze) to direct heat away from the motor, and exchange heat with seawater.

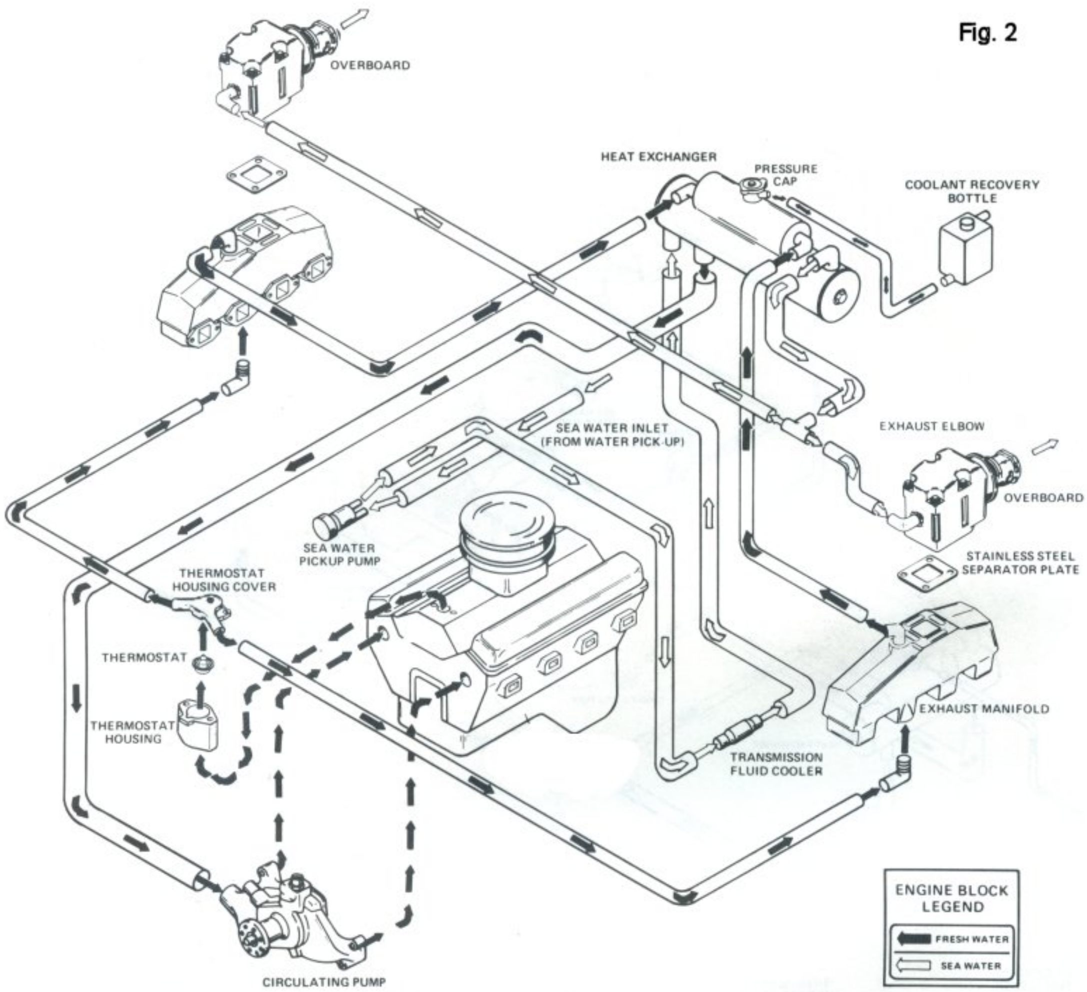
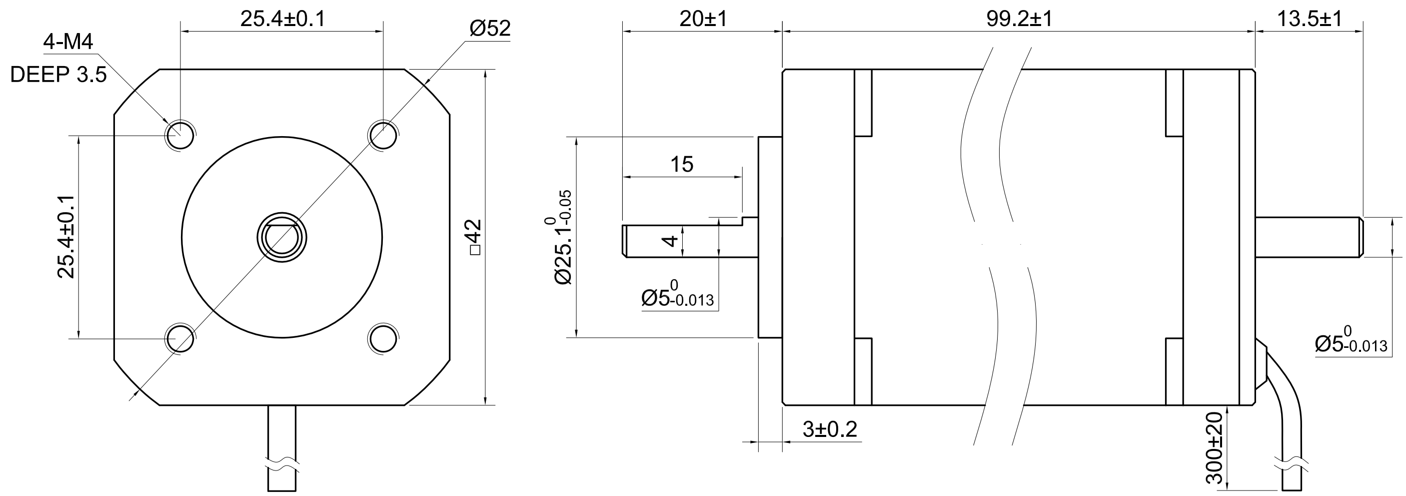


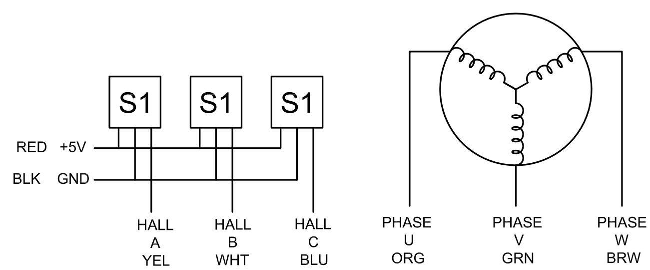
Figure A.18: Boat inboard motor cooling system [141]

A.13 Motor and Component Specifications

A.13.1 Specification for the Brushless DC Motor 24V 4000RPM [37]



SPECIFICATION	VALUE
NO. of PHASES	3
NO. of POLES	4
RATED VOLTAGE(V)	24
RATED CURRENT(A)	6.4±10%
RATED POWER(W)	105
RATED SPEED(RPM)	4000±10%
RATED TORQUE(mN.m)	250
NO LOAD CURRENT(A)	0.6
NO LOAD SPEED(RPM)	5900
SENSOR	HALL SENSOR
INSULATION CLASS	CLASS B
INSULATION RESISTANCE	100MΩ MIN @ 500VDC
DIELECTRIC STRENGTH TEST	500VAC for 1 MINUTE
BEARING TYPE	NMB BALL BERRING, C3



HALL LEAD: UL 1007 26AWG

PHASE LEAD: UL1007 18AWG

STEPPERONLINE Motors&Electronics

	APVD		
	CHKD		
1.5:1	DRN		
SCALE	SIGNATURE		DATE

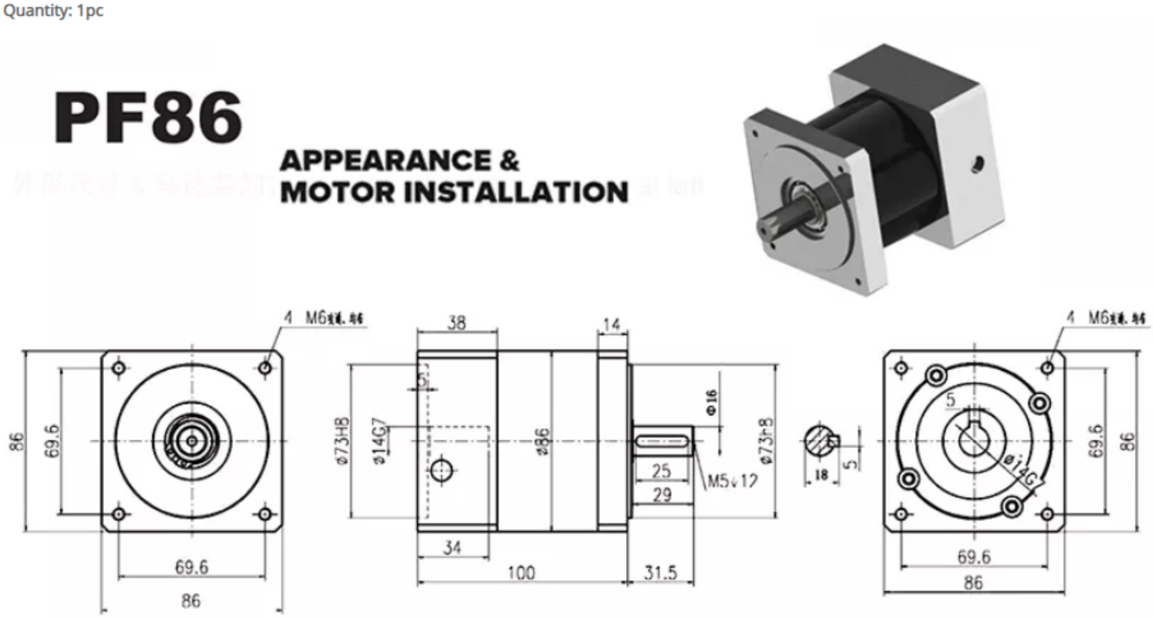
BRUSHLESS DC MOTOR

42BLS100-24-01

A.13.2 Specification sheet for the planetary gear [43]

Description:
Planetary Gearbox Speed Reducer Gearbox Gear Ratio 4:1 5:1 10:1 15:1 20:1 25:1 30:1 40:1 50:1 80:1 100:1

Specification:
Material: Metal
Gearbox Type: Planetary
Adapter motor: for Nema 34 Motor
Gear Ratio: 5:1, 10:1, 50:1, 100:1
Quantity: 1pc



Package Included:
1x Planetary Gearbox

Kindly Note:
1. Make sure the motor connect to a constant current or chopper drive controller before you test motor. Connecting the motor directly to a power supply will destroy the motor.
2. The colors may have difference due to different display. Thank you for your understanding!

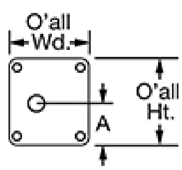
Figure A.19: Gearbox Specifications [43]

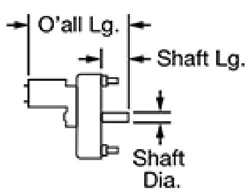
A.13.3 Specification sheet for the DC gearmotor [49]

Compact Square-Face DC Gearmotor

12V DC,0.6 rpm At 50 in.-lbs. Torque

$62.74 Each
6409K11



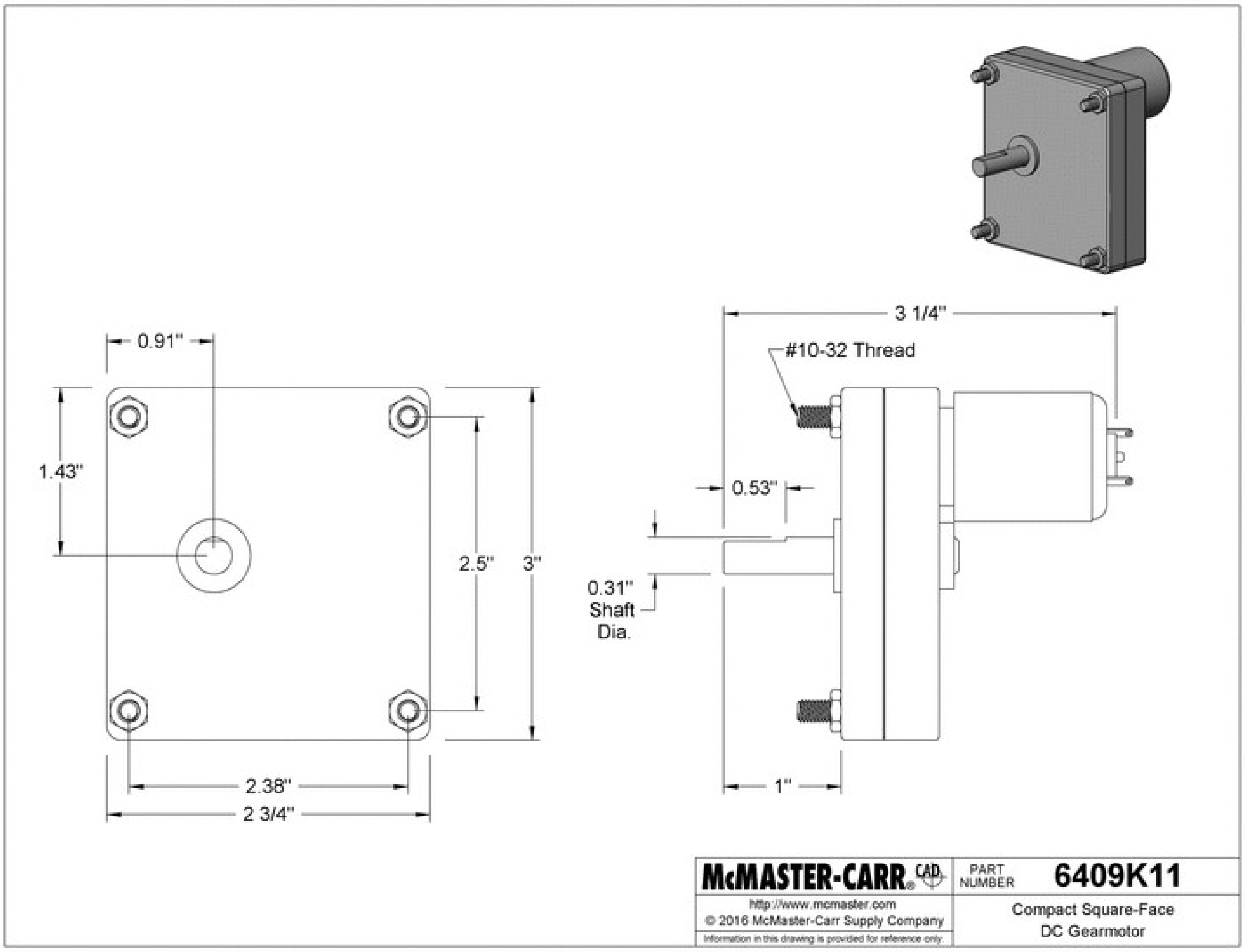


Maximum rpm	1
rpm @ Continuous Operating Torque	0.6 rpm @ 800 in.-oz.
Starting Torque	800 in.-oz.
hp	0.0003
Amps @ Full Load	0.1
Electrical Connection	Terminal Lugs
Overall	
Length	3 1/4"
Width	2 3/4"
Height	3"
Shaft	
Diameter	5/16"
Length	1"
Center to Base (A)	1.43"
Shaft Rotation	Clockwise or Counterclockwise
Shaft Type	D-Profile
Shaft Orientation	Parallel
Performance Rating	Continuous Duty
Motor Type	Brushed, Permanent Magnet
Service Factor	1
Enclosure Material	Die Cast Zinc
Gear	
Type	Spur
Material	Acetal, Metal
Bearing Type	Sleeve
Insulation	
Class	B
Maximum Temperature	266° F
Mounting Orientation	Horizontal, Vertical, Inverted, Any Angle
Mounting Location	Face
RoHS	RoHS 3 (2015/863/EU) compliant

Drive low-speed, high-torque applications in small spaces. Gearmotors combine a motor and speed reducer to lower speed and increase torque. Wire for clockwise or counterclockwise rotation.

Use amotor speed control(notincluded) to adjust the motor speed.

To convert AC power to DC power, see AC to DC transformers.



The information in this 3-D model is provided for reference only.

A.13.4 Specification sheet for the gearmotor [50]

Technical Specs

Nameplate RPM	1.3	Max. Ambient Temp.	40 Degrees C
Max. Torque	710 in-lbs	Overhung Load	900 lbs.
Item	DC Gearmotor	Gear Type	Hardened Steel, 1st Stage Helical, Subsequent Stages Spur, AGMA Class 9
Thermal Protection	None	Housing Material	Die Cast Aluminum
Full Load Amps	0.30	Overall Length	11-3/4"
Bearings	Needle Throughout with Thrust Balls on Case, Ball on Motor	Motor Type	Permanent Magnet DC
Shaft Dia. (Dimension U)	3/4"	Gear Material	Hardened Steel
Gear Ratio	1,413:1	Reversible Shaft Output	No
Input HP	1/20	Gearmotor Enclosure	Totally Enclosed Nonventilated
Shaft Length (Dimension V)	1-7/8"	Gearmotor Mounting Position	All Angle
Seals	Spring Loaded Lip Type on Input and Output Shaft	Gearmotor Shaft Type	Single
Gear Case	Die Cast Aluminum	Gearmotor Shaft Orientation	Parallel
Lubrication	Permanent Heavy Fluid Gear Oil	Gearmotor RPM Range	0 - 15
Dimension A	9.83"	Gearmotor Type	DC Gearmotor
Brushes	Externally Replaceable	Gearmotor Voltage	90VDC
Replacement Brushes	DTN6YHY3	Gearmotor Rotation	CW/CCW
Dimension H	4.10"	Standards	UL Recognized, C-UL Recognized
Dimension D	2.58"	Rear Shaft Encoder/Pulse Generator Mounting	Yes
Length Less Shaft	9-7/8"		

Figure A.20: Acklands Grainger 90VDC Gearmotor Specifications Sheet [50]