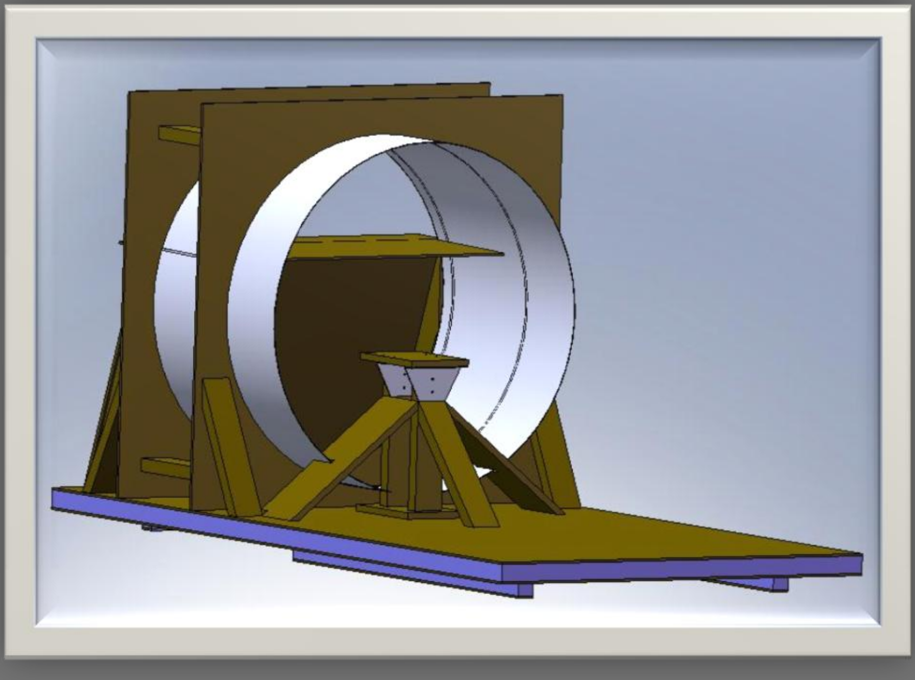
Design and Construction of a Passenger Hovercraft

E90 Final Report

Kofi Anguah
Nick Szapiro

05/08/2009



Advisor: Professor Nelson Macken

Contents

Abstract

The purpose of our senior design project is to construct a functioning hovercraft designed through fundamental principles. Through this design project, we explore the process of engineering from initial design to product construction. We were forced plan around material limitations and time constraints. We produced a vehicle capable of hovering and forward motion.

Introduction

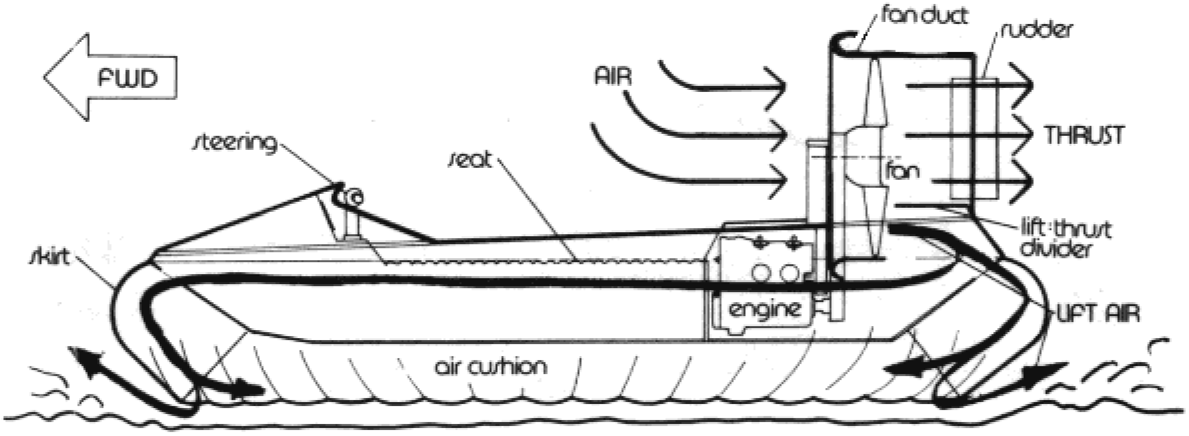


Figure 1: (http://www.hovercraftdealer.com/Download4.html)

A hovercraft is a vehicle capable of traveling over most surfaces on a cushion of air trapped under the body for lift. Air propellers, water propellers, or water jets usually provide forward propulsion. Air-cushion vehicles can attain higher speeds than can either ships or most land vehicles due to lower frictional forces and use much less power than helicopters of the same weight. Figure 1 above illustrates the operational principles and basic components of a typical hovercraft.

Specifically for our hovercraft, there are three main design groups: the lift, thrust, and steering systems. The arrangement of the hovercraft is similar to that shown in Figure 1. The propeller shown must be designed for a vehicle as typical fans act by creating vortices to mix the air, reducing the ejected air's translational kinetic energy and significantly reducing efficiency. We outline key features of the three main groups below.

Lift System

The hovercraft relies on a stable cushion of air to maintain sufficient lift. The air ejected from the propeller is separated by a horizontal divider into pressurized air utilized for the air cushion and momentum used for thrust. The weight distribution on top of the deck is arranged so that the air is distributed the air from the rear of the deck throughout the cushion volume in an approximately even fashion to provide the necessary support. The skirt extending below the deck provides containment, improves balance, and allows the craft to traverse more varied terrain. We maintain the rigidity of the skirt by filling the air-tight skirt with the same pressurized air diverted towards lift.

Thrust System

The air not directed to the cushion and skirt is propelled backwards, providing forward thrust to the craft. The size of the propeller, rpm output of the engine, and height of the lift/thrust divider are the determining parameters for the thrust force. A thrust duct channeling the air into the propeller can provide up to a 15% increase in efficiency [Universal Hovercraft]. The limiting factor for the thrust is the air flow available to direct backwards since our primary concern is providing pressurized air for air cushion and lift. As a result, our forward speed is limited but maintainable.

Steering System

Since a hovercraft lacks the same frictional and drag effects as boats or cars, steering must be approached without precise control in mind. This is especially true in our case as the power supply is limited. Rudders are a main source of steering and are attached to the rear of the duct to direct the flow of air and the direction of the subsequent momentum transfer from the air to the craft. The driver controls the movement of the rudders through a joystick located in the front of the craft. A throttle on the engine situated next to the driver allows him to vary the speed of the craft, allowing for a smaller radius of turning once proper driving techniques are mastered. Because of the air cushion effect, the driver may influence the steering by shifting his weight nearer to any of the four sides of the deck. For example, a shift right turns the hovercraft to the right.

In the remainder of the report, we discuss our design and construction processes, the results from testing the craft, the problems associated to our design and construction, and possible improvements.

Design

The driving requirement of the hovercraft is the ability to hover given the combined weights of a passenger, engine, duct, wood supports, skirt, deck, and propeller in order of decreasing magnitude. So, we must determine the necessary power to satisfy our expected general requirements. We calculate this power demand through the use of Bernoulli equations to track the energy changes of the air in passage through the propeller, into the air cushion, and out the skirt. These locations correspond to points 1, 2, and 3 in Figure 2 below:

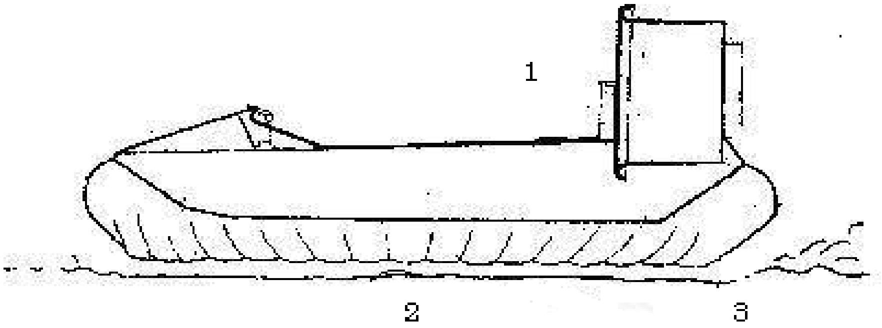


Figure 2: (www.discoverhover.org/infoinstructors/guide4.htm)

We begin our considerations by determining the necessary power for static lift. If we assume that all of the air through the propeller goes into the air cushion and model the flow of air with Bernoulli equations ignoring frictional losses, we see that

$$\frac{v_1^2}{2} + gz_1 + gains_{1-2} = \frac{P_2}{\rho} + k_L \frac{v_1^2}{2} \; with \; k_L = .5_{sharp\ entry} + .3_{90^0\ bend} + 1_{exit}$$

$$\frac{P_2}{\rho} = \frac{v_3^2}{2} \; with \; P_2 = \frac{Total\ Weight}{Deck\ Surface\ Area}$$

Note that the velocity associated to the minor losses through the propeller and duct are associated with the velocity through the duct since this is the only relevant velocity available from calculations. From these equations, we can determine the energy gain needed from the propeller. To proceed, we need a rough but representative idea for the shape of the hovercraft and the expected payload.

During the first stages of our design, a variety of ideas seemed feasible and appealing. Our task was to decide on the best design for our goals. Of all of the designs, there were four serious alternatives to our eventual final design: a circular deck, power by leaf blowers, a non-horizontal propeller and a two engine, two propeller craft. The appeal of the circular deck is that the surface area of the deck is maximized for the amount of material used so the lift is maximized. The fatal drawback for a circular deck with only one propeller that is dedicated to lift was the inability to move reliably. There is no orientation to the craft and the only apparent way to move was by shifting the weight of the driver on the deck, a very limited idea. Although the flexibility of a design involving leaf blowers impressed us with the room for creativity and originality, the number of leaf blowers required for proper functioning due to the low density of air was awkward and somewhat prohibitive. A hovercraft with a tilted propeller is shown below:

Figure 3: http://www.hovercraft.com/content/index.php?main_page=index&cPath=33_39

The rationale for such a design is to have most of the air from the propeller dedicated to lift while directing some air out of the back of the skirt for thrust. However, directing thrust air first through the cushion adds significant losses and creates large inefficiencies. As can be seen from the figure above, this design is only suited to small, children's crafts. The last alternate design involves having independent systems for lift and thrust. The benefits are greater power input into the system and having components designed fully and specifically for a given purpose. However, such a system is much more complex and expensive. In order to better understand hovercraft design for our scale of a craft, we purchased three sets of plans from Universal Hovercraft – a tilted propeller, a two engine model, and a single horizontal propeller. After examining the plans and the benefits and drawbacks for each type of hovercraft, a rectangular hovercraft with a horizontal propeller was deemed most appropriate since there is an orientation to the craft with direct thrust and a total cost within our constraints.

A significant resource and obstruction to initiating and finalizing a design is the initially large number of free variables involved in these calculations. Because of this freedom, we use an iterative process to find a set of dimensions satisfying our general requirements for having a passenger hovercraft with a horizontal propeller supplying both lift and thrust. The following description is an example cycle in the iterative process. Since plywood comes in 4’x8’ sheets, we fit the size of the deck to these dimensions for the sake of simplicity. The total expected weight of the craft is obtained by summing the individual weights of all components such that, in pounds,

$$Total\ Weight = 200_{passenger} + 50_{engine} + 25_{shroud} + 10_{skirt} + 40_{deck\,/supports} = 325\ lb$$

We have now fixed the necessary air pressure in the cushion. From the Bernoulli$_{2\text{-}3}$, we see that we have also fixed the escape velocity of the air out the skirt. If we decide how high we want the hovercraft to hover off of the ground, i.e. the clearance height of the bottom of the skirt above the ground, we fix the volumetric flow rate out of the cushion under the skirt. Assuming incompressible flow, we can multiply the mass flow rate of the escaping air by the air’s kinetic energy to obtain the power needed to pressurize the cushion at a certain clearance height for a given weight load on a deck of specific area. This is the power needed to maintain the pressure in the cushion. For our craft, the series of calculations is as follows:

$$P_2 = \frac{325lb}{4ft \cdot 8ft} = 10.2\ lb/ft^2$$

$$v_3 = \sqrt{\frac{2 \cdot 10.2lb/ft^2}{.002377slugs/ft^3}} = 92\ ft/s$$

$$For\ h = 1\ in., \dot{m} = .002377slugs/ft^3 \cdot \frac{1}{12}ft \cdot 2(4ft + 8ft) \cdot 92ft/s = .437\ m^3/s$$

$$Power = .437\ m^3/s \cdot \frac{(92ft/s)^2}{2} \cdot \frac{1\ hp}{550\ ft \cdot lb/s} = 3.4\ hp$$

It turns out that the energy losses in "bending around the pipe" 1-2 are counterbalanced by the loss of potential energy so that the Bernoulli$_{1\text{-}2}$ is negligible. We now consider approximate inefficiencies of our system to check whether these component specifications are satisfactory.

It is important to note that we should be wary of designing based solely on this power requirement given our simplifying assumptions. The two most critical elements present in any final design but missing from the considerations above are that we must specify the power requirements of the engine (not the propeller), and some air will be diverted for thrust instead of lift. At best, the propeller is about sixty percent efficient while the power diverted to thrust is proportional to the flow not trapped by the air box.

These inefficiencies and multiple roles tally up quickly so we decided that an engine in the range of 8-12 hp would be appropriate for our small thrust needs. Because a 10 hp engine costs ~$450 and we received a generous $500 grant from the Philadelphia chapter of ASME, a Tecumseh 10 hp gas engine was purchased for the project. Based on the recommendations of Don Miller - currently at Arrowprop Company - who has been in the propeller business for 45 years, the proper matching of the torque of our 10 hp engine is to a 36-42 inch diameter propeller. Because we were unsure of the amount of vibration of the engine, especially when loaded with a propeller, our inclinations leaned towards the smaller diameters for both safety and structural concerns. A larger propeller also increases the fluctuations resulting from the misalignments of leveling along various axes during construction. Given a 36-in. propeller, we needed the surrounding duct to have a minimal chance of contact with the quickly spinning blades. As such, we constructed the duct with two inches of clearance around the blade to account for the vibration of the propeller and our own construction tolerances. This clearance area was later reduced in front of the propeller since there was sufficient area between the propeller tip and the duct to allow air to escape back towards the front of the duct further reducing the efficiency of the propeller.

Construction

Below is the detailed outline of the construction process we used. Each section is accompanied by a detailed schematic diagram detailing the dimensions of the materials used as well as pictures taken during construction. A listing of the materials used, their costs and sources can be found in the appendix.

Deck

(Refer to the Deck and Bottom View blueprints in the appendix)

1. The deck is composed of a 4’ X 8’ X 2” rectangular piece of blue foam sandwiched between two pieces of 4’ X 8’ X 0.25” plywood. The layers of plywood prevent the degradation of the foam by shear and forcible contact while the foam provides rigidity and strength will little additional weight.
2. To join the three layers of the deck together we used Green Choice construction adhesive, a strong and adaptable glue. We first attached one side of the plywood to the foam, then the other side. We ensured that the edges of the foam and the plywood aligned well. While doing this we ensured that the perimeters of the two materials were glued together firmly since this was the likeliest area to separate. To facilitate the bonding of the three materials, weights were placed in an evenly distributed manner on the top surface of the top piece of plywood. The deck was left to dry overnight. The glue instructions state that 6-8 hours are needed until the bond has formed properly.
3. A rectangular 15” X 2’ hole was cut 14” from the back edge of the deck so that air could travel through the duct into the cushion. This lift hole was centered along the width of the deck since, for stability and control, there should be no preferred direction for the movement of air into and throughout the cushion. The location of the lift hole fixes the positions of the rest of the

components within about half a foot since we attempt to minimize material usage due to weight considerations.

4. The two holes the sizes of 2'' X 4''s for the engine support posts were then cut into the deck 21" from the right edge of the deck. These posts were not centered on the deck since the shaft of the engine was not centered above its base. Our goal was to center the propeller on the deck, not the engine, in order to center the thrust generated as well as fill the air cushion evenly. Because of the shifted shaft, the wider edges of the post were aligned to resist the lateral motion and vibrations stemming from the skewed symmetry. Figure 4 below shows the deck during construction.

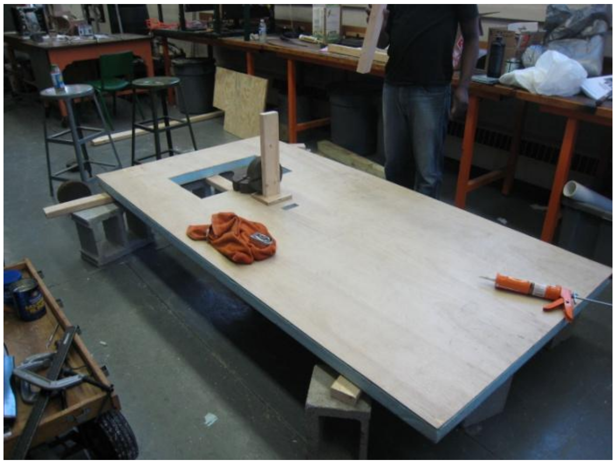


Figure 4: Deck after construction with lift and engine mount holes cut in it

Engine Mount

(Refer to the Engine Mount blueprint in the appendix)

1. In order to connect the independent, vertical engine posts to each other and the deck, we obtained an 11" X 7" X 3/4" piece of plywood and cut two rectangular holes measuring 3.5" X 1.5" in it. This piece anchored the base of the engine mount.

2. Two wooden posts measuring 19.75” X 3.5” X 1.5” were cut and placed through the holes in the piece cut in the previous step. The height of the posts must be sufficient to ensure that the shaft of the engine clears the deck by more than the radius of the duct.
3. Green Choice construction adhesive was applied to the sections of the engine posts inserted into the holes in the deck (See Figure 5). The posts were then inserted through the holes in the anchoring piece of wood and the deck such that the ends of the posts were flush with the lower surface of the deck. Care should be taken to have the posts rise without tilt from the deck so as to improve the chances of having a level engine. Weights were placed on the wood supporting the posts on the deck to force the glue underneath it to be distributed evenly and then left overnight to dry as shown in the Figure 5.
4. After drying, six layers of fiberglass were applied across the top surface of the wood supporting the engine mount posts and the deck around its perimeter. Six more layers were applied at the joint between the engine mount posts and the supporting wood. The deck was left to dry overnight.

We now provide a brief introduction to our method of fiberglassing. The necessary components are fiberglass cloth, resin, hardener, brushes. We mix the resin and hardener to the weight proportions specified by the product and use the liquid mixture to adhere the cloth to the wooden surface. We cover the cloth with glue until the glue imbeds itself into the fibers and the cloth turns clear. In order to improve the strength of the fiberglass, we make sure to conform the cloth to the shape of the joint being strengthened while layering the cloth at a variety of angles to ensure strength in all directions. Care must be taken to have minimal contact with the carcinogenic hardener while mixing and covering the fiberglass with glue. The strands of fiberglass can also be very irritating if imbedded in clothing. If working in a poorly aerated space, make sure to use masks to prevent overexposure to fumes. If for no other reason, proper ventilation of the fiberglassing space is beneficial as the smell is rather pungent.

5. The supporting plate for the engine was placed on the engine mount posts. To make it level, two notches were cut to fit the vertical posts in the lower surface of the top plate. These notches were used to ensure a tight connection before fiberglassing was to fix the joint. We used these notches to level the surface by squeezing varying quantities of glue into the pocketed space until the bubble level on the plate showed a level surface. The glue had an additional benefit of improving the connection between the posts and the plate.
6. Four holes were then drilled through the top plate of in order to bolt the engine to the plate. The locations of the holes must be precise as these determine whether the shaft will be skewed with respect to the deck and the duct.

Figure 4: Applying adhesive to engine mount post

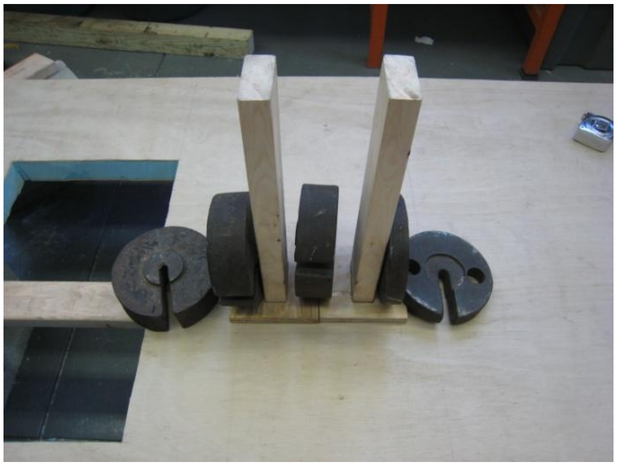


Figure 5: Weighing engine mounts after applying adhesive

Duct

(Refer to the Side View blueprint in the appendix)

1. In the interests of speed and simplicity, our duct was an un-tapered cylinder obtained by rolling a sheet of thin Aluminum. The duct was made out of a 126” X 28” X 1/16” piece of Aluminum. A 15” X 24” rectangular hole and a 5” X 3.5” rectangular hole were then cut to accommodate the lift hole and engine mount post in it in the positions shown in Figure 8.
2. In order to mount the duct to the deck, we used two plywood rectangles as frames. A 4’ X 8’ X 3/8” piece of plywood was obtained and cut in the middle to obtain two pieces of plywood each 4’ X 46”’ X 3/8”. Given the fixed height of the engine, we knew the exact height the middle of the duct needed to be above the deck.
3. Using an electric jigsaw, 40” diameter circles were then cut out of the two pieces of plywood. These holes were centered along the width of the plywood pieces.
4. To make a cylindrical frame with which to roll the aluminum into the desired duct shape, we joined the two circular pieces cut in the previous step using four pieces of wood measuring 28” X 3.5” X 1.5”.
5. We then rolled the aluminum around the wooden frame leaving a 1” overlap and held the cylinder in shape using a tightened ratchet strap.
6. We then marked a straight line along the length of the frame, ½” from the edge of the overlap. Along this line, we drilled a series of holes through the aluminum. Bolts and nuts were then used to fasten the aluminum together to maintain the cylindrical shape of the duct. This must be at least a two man job as the aluminum is difficult to bend and maintain as a circular form.

Duct Support Frame

(Refer to the Side View blueprint in the appendix)

1. Given that we used the circles cut out of the support frames to roll the aluminum, using the support frames of the duct was the obvious choice because their dimensions allowed us to fit the rolled aluminum duct tightly in them.
2. After removing the cylindrical frame from inside the aluminum, we fit the duct through the wooden support frames, leaving one frame on each end of the duct, and mounted the duct assembly on the deck. The rear support frame was aligned with the rear edge of the lift hole while the front frame was positioned such that it was over the approximate location of the propeller. This was done because it was important to ensure that the duct was very rigid near the propeller given that we did not know how the duct would vibrate when operational and deform over time.
3. The duct was positioned in the support frames such that the large hole was directly over the lift hole and the notch in the front was in contact with the rear engine mount post. This was done to ensure that the propeller was adequately imbedded within the duct such that turbulence around the propeller tips would be reduced and the efficiency of the propeller would be improved. We wanted none of the turbulence resulting from entering the duct to affect the propeller.
4. The support frames were glued in position using Green Choice construction adhesive and three layers of fiber glass applied using the method previously described. Refer to Figures 6, 7, 8 and 9 for pictures of the mounted duct assembly.

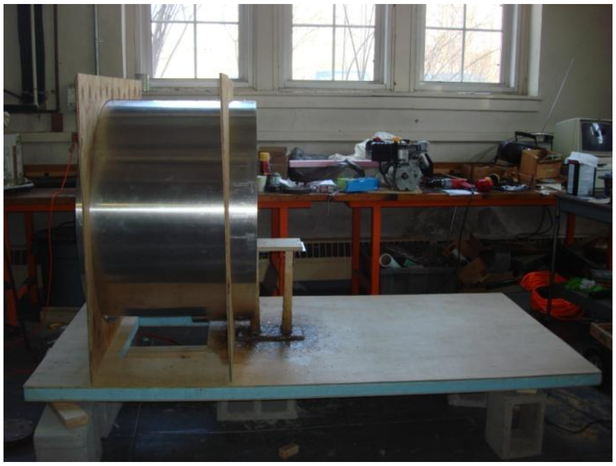


Figure 6: Duct assembly after mounting on deck

Figure 7: Rear view of mounted duct assembly

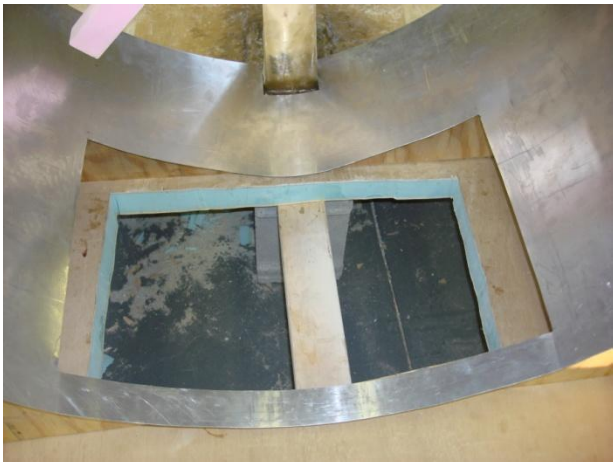


Figure 8: Inside of duct assembly after mounting

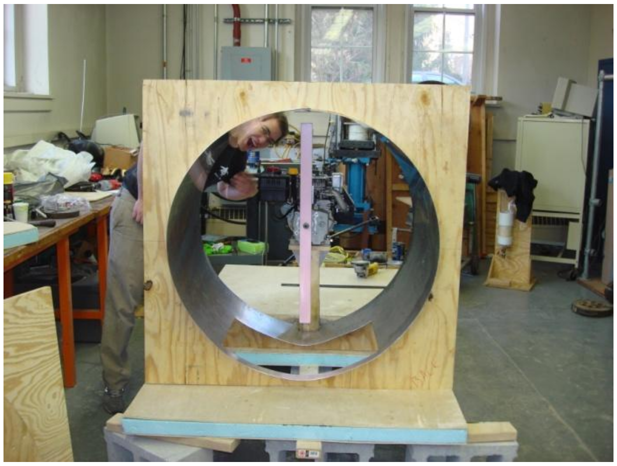


Figure 9: Rear view of duct assembly

Engine Mount and Duct Frame Supports

(Refer to the Side View and Front View blueprints in the appendix)

1. After mounting and securing the duct assembly on the duct, we cut and glued the angled supports for the engine mount in place. Six layers of fiberglass were applied to the joints between the engine mount supports, the deck and the engine mount posts. The same number of fiberglass layers was also applied to the joints between the top plate of the engine mount and the engine mount posts (See Figure 11). We used the most layers of fiberglass in the joints around the engine because we expected them to bear the most stress when the engine was operational.
2. To further strengthen the engine mount, two gusset plates were mounted at the joints between the top plate of the engine mount and the engine mount posts (See Figure 12). In addition to the extra strength obtained through these gussets, they act as a mild safety check since they would not likely fracture in failure as would the fiberglass.
3. We then installed four angle supports with glue and fiberglass between the outside of the duct frame and the deck and four horizontal supports were screwed between the two support frames (See Figure 10). This was done to increase the rigidity of the duct assembly.

Figure 10: Side view of duct assembly showing supports for duct support frames

Figure 11: Fiberglassing engine mount supports

Figure 12: Engine mount supports after fiberglassing

Skirt Assembly

1. To inflate the skirt, a second hole, 30” X 1” was cut in the rear of the deck. This hole was centered along the width of the deck and positioned 1” from the rear edge of the deck.
2. The skirt material consisted of four strips of vinyl coated nylon, one for each side of the deck. The pieces along the length of the deck measured 30” X 128” while those along the front and rear of the deck measured 30” X 80”. To allow air to flow from the skirt hole and inflate the skirt around the edges of the skirt, it was necessary to have the joints of the skirt constructed in a fashion would not impede the flow of air. If we fold a typical shape into a right angle, odds are the corner will be pinched. We used a pattern obtained from Universal Hovercraft (see Figures 13 and 14) to trace the outline of the curved edges at the corners of the pieces of skirt material so that when joined the corner would act as expected.
3. At each corner, we overlaid the curved ends of skirt material on top of each other and glued them using vinyl cement. The vinyl cement was applied evenly on a 1” strip along each of the curved edge and left for about 2-5 minutes to harden before the two edges were brought together. According to the manufacturer’s specifications, vinyl cement needs to be left between 2 to 5 minutes after application depending on the surrounding temperature before being used

to join surfaces. As such, we used a sample of the skirt material to determine the appropriate waiting time before joining the skirt materials together during each gluing session.

4. To fasten the skirt to the deck, we applied a one inch thick layer of vinyl cement along each edge of the lower surface of the deck as well as the outer perimeter of the skirt material. Then after waiting 2-5 minutes, we pressed the skirt material firmly to the deck to glue the two surfaces together and then, using a staple gun, stapled through the skirt material into the deck to fasten the two materials more securely.
5. After attaching the outside perimeter of the skirt to the deck, we applied another strip of vinyl cement 1” wide along the inside edge of the skirt material and on the deck 1” away from where the outside edge of the skirt had been attached. Then we fastened the two surfaces together in the same manner as for the outside perimeter of the deck. When constructing the skirt, care was taken to use the least amount of deck surface area to fasten the skirt to the deck so as to minimize the reduction of surface area available for lift, hindering stable operation of the craft. After cutting the skirt sections, we discovered that they were longer than the sections of the deck. As a result, we had to create folds in the skirt before attaching the inner perimeter to ensure that the skirt fit the perimeter of the deck in order to prevent leakages. Refer to Figures 13 to 20 for photographs of the skirt construction process.
6. After constructing the skirt, we tested it using an air pump to ensure that it had no leaks.

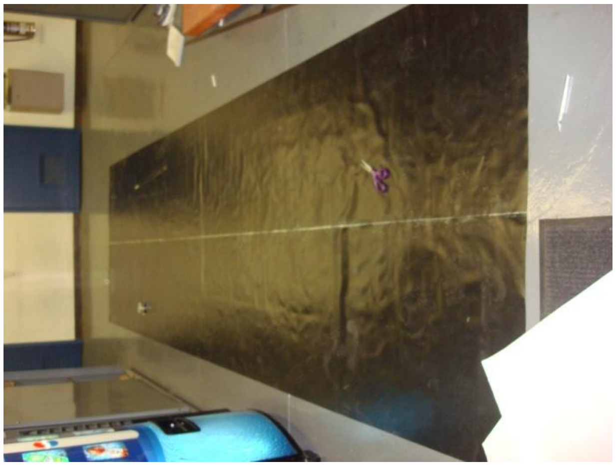


Figure 13: Skirt material before sketching

Figure 14: Sketching skirt pieces on the skirt material

Figure 15: Skirt material after sketching of skirt pieces

Figure 16: Front and rear skirt pieces after cutting

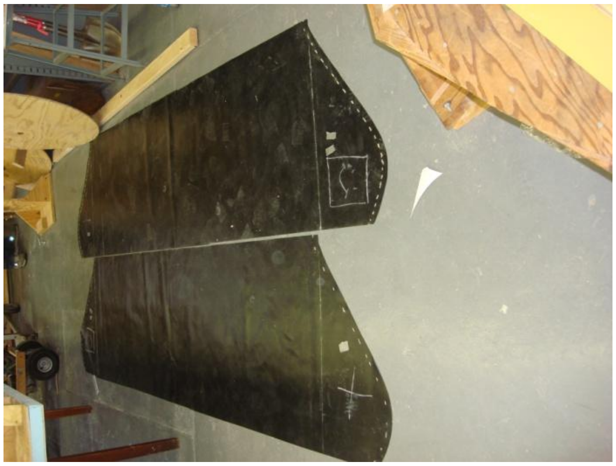


Figure 17: Side skirt pieces after cutting

Figure 18: Section of outer perimeter of skirt after attaching to deck

Figure 19: Skirt assembly after attaching outer perimeter to deck

Figure 20: Completed skirt assembly

Engine Testing

1. After constructing and attaching the skirt, we mounted the engine on the engine mount and bolted it firmly in place. Then we ran it to check whether the engine mount was strong enough to withstand the vibrations.
2. The propeller was then attached to the shaft using a taper lock, making sure that there was enough clearance between the tips of the propeller and the duct. We then started the engine to ensure that the engine mount was strong enough to withstand the increased load and that everything was well aligned. Refer to Figures 21 to 23 below for photos of this construction process.

Figure 21: Engine and propeller mounted on engine stand

Figure 22: Testing propeller in duct

Figure 23: Testing of propeller in duct

Air box

(Refer to the Side View and Duct and Air Box View blueprints in the appendix)

1. To determine the appropriate height of the air box to trap enough air for lift in the air cushion and for thrust, we experimentally varied the height of the air box. We did this using Unistrut mounted to the rear duct support frame and bolted to a piece of plywood placed horizontally in the duct. The rear of the duct was then covered up to the appropriate heights using plywood which was then supported by weights to hold in place against the force of the air ejected by the propeller (See Figures 24 and 25). We were looking to find the lowest height of the splitter capable of providing sufficient lift so that the amount of thrust is maximized.
2. Two pieces of plywood were used to seal the gaps between the sides of the lift holes and the hole in the duct (See Figure 26). This was necessary to ensure that all the trapped air travelling through the hole in the duct was forced into the bottom if the craft. The joints created were fiberglassed to seal against air leakage.
3. In experimenting, we used an air pump to fill the skirt separately while the blocked air from the propeller was used to fill the air cushion below the craft. After four trials, we determined that a splitter positioned 26” from the bottom of the duct was the lowest height that allowed us to

hover. At this height, 2/3rds of the height of the duct was covered. We based the final air box design on this parameter and after gluing the components in place, strengthened the joints using six layers of fiberglass. We decided this was necessary to provide enough support for the air box to withstand the force of the air blowing from the propeller and the vibrations of the craft. Interestingly, the entire craft ran much more smoothly once the final pieces were in place as it is clear that, when not fully fixed, semi-loose pieces adversely affect the flow of air. The propeller and engine shook much less once the air box was fiberglassed in place. Refer to figures 27 to 29 for photographs of the completed air box.

Figure 24: Rear view of air box during testing

Figure 25: Testing of air box

Figure 26: Construction of final air box design

Figure 27: Side view of air box after construction

Figure 28: Rear view of air box after construction

Figure 29: Front view of hovercraft after constructing air box

Fixing the Clearance Gap around the Propeller

One of the more clear alterations involved reducing the clearance area between the duct and the propeller tips. As could be noticed by moving a string across the entrance cross section of the duct, the air around the edges of the duct actually traveled opposite the direction dictated by the propeller. Given that the majority of the air expelled from our propeller should flow closer to the duct wall, this effect was likely to have been highly detrimental. However, by reducing the clearance area in front of the propeller, we prevented air from “turning around” as easily. Qualitatively it was clear that all of the flow was into the duct with the restriction in place. The clearance gap was reduced by fixing a hose with a 2” diameter around the inside of the duct. The hose was positioned approximately 2” in front of the propeller to ensure that it did not hit the propeller when it was in motion. Refer to Figure 30 below for a photograph of the fixed clearance gap.

Figure 30: View of duct after clearance area was reduced.

Rudder System

We created the final rudder system design with the help of Julia Luongo as part of her E83 project by adjusting some ideas from Jesse Bertrand and James Beall's E14 project to fit our specifications. See the appendix for a copy of the E14 project report.

1. The steering system of the hovercraft utilizes two rudders mounted on top of the air box, in the path of the thrust airflow. The rudders were bracketed to wooden dowels which can rotate to direct air flow. To construct the rudders, two plywood rudders were cut with dimensions of 14''x16''x0.5'' a small 0.5'' hole was cut into a corner of each rudder. Then we cut a wooden dowel of 1'' diameter is cut into two segments, each 17'' long. Two 3'' long wooden 2''x4'' as well as two 5.5'' long piece of 2''x4'' were cut.
2. The splitter which forms the top of the air box has a 4'' overhang past the back of the air box. The splitter was a piece of plywood 0.5'' thick. Two holes of 1'' diameter were cut as close to the edge of the splitter overhang as possible. Each hole was 14'' from the outside edge of the overhang.

3. Then we screwed the two 3’’ long pieces of 2’’x4’’ into the splitter underneath each hole. We then bored a hole of 1’’ diameter out of each 2’’x4’’, ensuring that these holes lined up with the holes through the splitter. When boring these holes, we ensured that they did not go entirely through the 2’’x4’’since the wooden dowels were meant to rest in them.
4. Next, the 5.5’’ long pieces of 2’’x4’’ were screwed into the duct support, 2.5’’ from the top of the support with the cut side touching the support so that the pieces extended 5.5’’ from the support. The 2’’x4’’s were placed directly above where the holes in the splitter. Before attaching the 2’’x4’’s, holes were bored all the way through each one so that the holes lines up with the holes in the splitter.
5. The wooden dowels were then threaded through the top 2’’x4’’ and rested inside of the hole though the splitter overhang. Then we clamped the rudders to the dowels, with the dowels placed 4’’ from the inside edge of the 16’’ side. The rudders were oriented such that the small hole in the corner of each rudder was on the outer bottom edge of the rudder.
6. Next, the pulleys were mounted. One question in the design process was how many pulleys should be used. The path of the rope to the driver needed to be as direct as possible in order to avoid excessive turns, while not take any sharp turns that could risk the rope rubbing against anything and wearing out. It was decided that 3 pulleys on each side was sufficient. One pulley to bring the rope around the first duct support, one pulley to bring the rope down along the deck, and a third pulley to bring the rope back to the center to the steering joystick. One pulley was mounted on each outside corner of the splitter overhang to aid the rope in turning the corner around the duct support. At the same height as the pulley, a washer with a 0.5’’ diameter was then attached to the duct support to guide the rope around the support. A pulley screwed into a piece of 2’’x4’’ was mounted on the next duct support to guide the rope downward towards the deck. Finally a pulley was then screwed into each outside edge of the deck, 38’’

from the front of the deck. These pulleys were angled towards the center of the deck so that they intersect in the center of the deck at a point 14.5’’ from the front of the deck.

7. The joystick, or tiller, was a 47’’ long wooden dowel with 1’’ diameter. The wooden dowel rested in a 2’’ wide piece of 2’’x4’’ which was attached to a door hinge. The other flap of the door hinge was screwed into a piece of 2’’x4’’ which was both screwed and glued on to the deck. The joystick is placed in the center of the deck, 14.5’’ from the front of the deck.
8. The last step was to thread a rope through the entire system. The rope needed go through the hole in each rudder, through the washer guide and through all of the pulleys. Each end of the rope met at the front of the hovercraft where the joystick was attached. The ends of the rope were pulled tight and then hose clamped to the wooden dowel. Then we placed stops on the rope on both sides of each rudder to prevent the rope from sliding through the hole in each rudder. Refer to Figures 32 to 37 for diagrams and photographs of the control system. The motion of the joystick is opposite to that of the rudders. In order to turn the hovercraft to the right, the joystick must be pulled to the left, and vice versa. This is illustrated in the following figure:

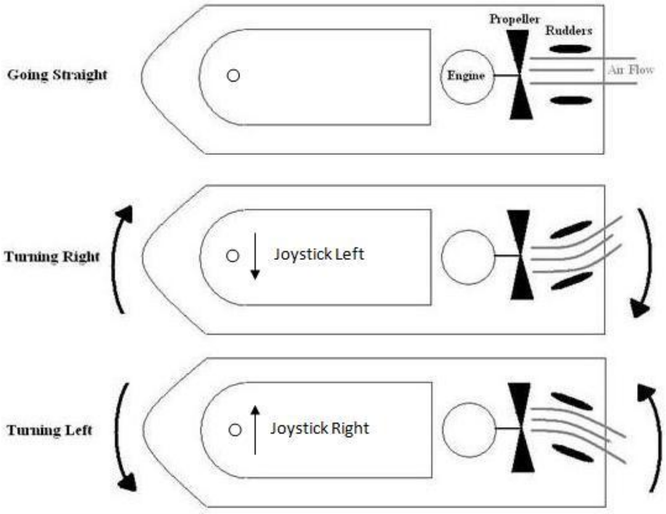


Figure 31: Rudder Control via joystick

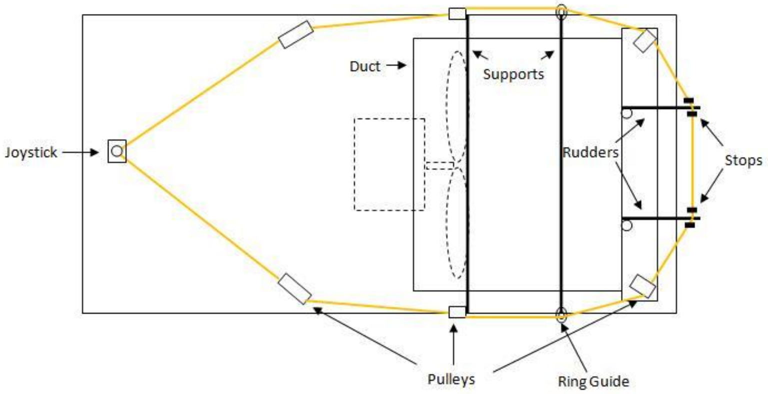


Figure 32: Overhead schematic of the closed loop rudder system

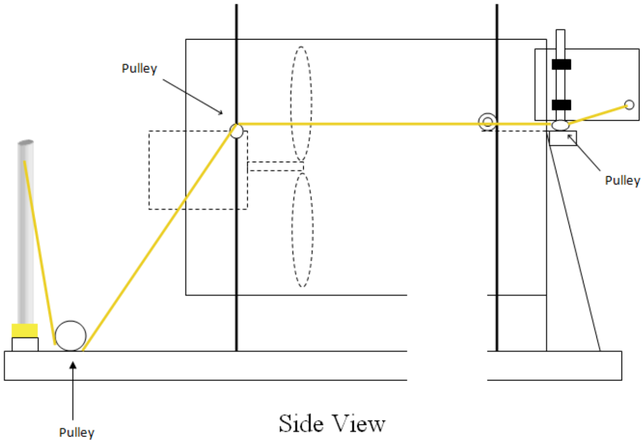


Figure 33: Side view schematic of the rudder system

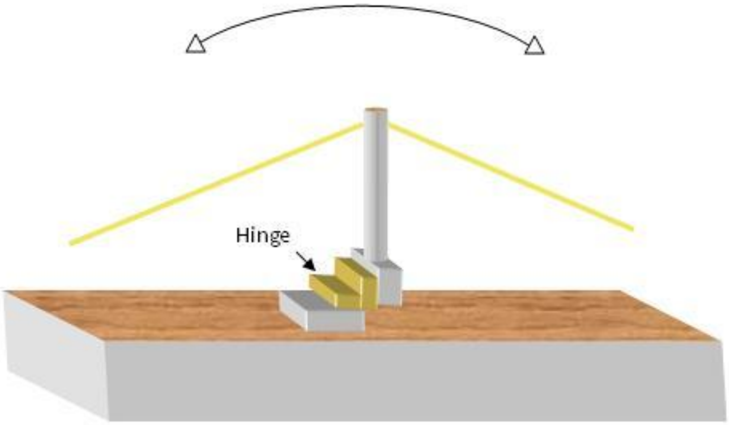


Figure 34: Diagram of joystick setup

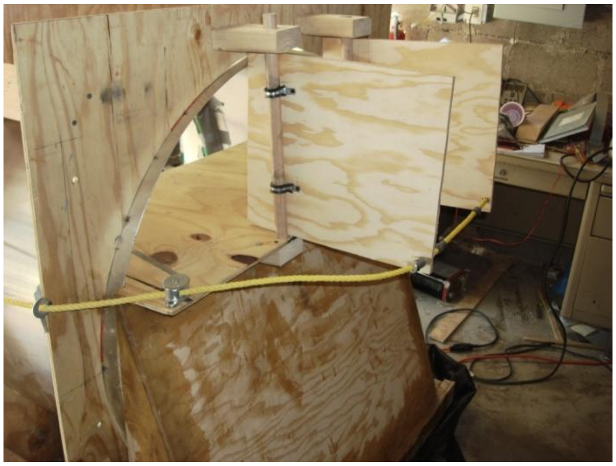


Figure 35: Rear view control system showing rudders, rope and pulley

Figure 36: Side view of control system showing pulleys and rope

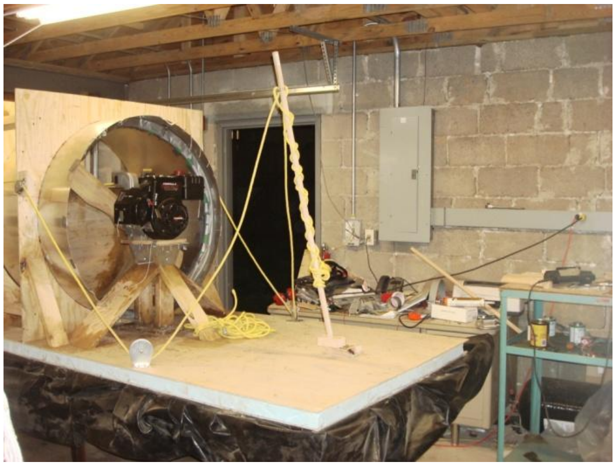


Figure 37: Front view of control system showing joystick, pulleys and rope

Fixing the Clearance Gap around the Propeller

As mentioned earlier in the skirt construction process, we had to create folds in the skirt material before attaching the inner perimeter of the skirt to the deck. These folds were made in order to prevent leakages because the skirt sections were longer than the respective sections of the deck to which they were attached. We made the folds near the front of the craft away from the hole in the deck. Unfortunately, we discovered that because we did not evenly distribute the folds in the skirt sections along the length of the deck, the skirt profile was uneven at the back near the duct. There was a section of the skirt on each side along the length of the hovercraft which was significantly higher. This was detrimental as a lot of air was lost from the air cushion during operation of the hovercraft, reducing our ability to hover correctly.

This problem was corrected by attaching sections of left over skirt material over the uneven sections of the skirt profile to compensate to the raised height along the profile. Further testing proved that this solution adequately reduced the air loss from the uneven profile, allowing the craft to hover higher at the full length of the skirt plus the clearance height. Figure 38 is a photograph of one section of the skirt after the fixing the uneven profile.

Figure 38: Skirt assembly after fixing unevenness in skirt profile

Results

Determining how well the hovercraft works consists of considering how well the craft performs as a whole and how well each component performs its task. The hovercraft achieved varying degrees of success with respect to its ability to hover and move. The hovercraft is capable of static hovering with over a 300 lb. payload on the smooth garage floor. A larger capacity was not tested because more weights were not available. The craft can hover and move forward on the garage floor with one passenger. Sustained and accelerating forward motion was achieved on a paved, downhill road with a passenger. The hovercraft was incapable of traversing grassy terrain or moving uphill gradients. So, the hovercraft was able to hover and move depending on the hardness, smoothness, and slope of the terrain so our basic goals were achieved.

We now consider the functioning of the components of our craft. The engine mount performs very well in supporting and constraining the engine while limiting its vibrations. The fiberglassed joints proved to be strong and the engine shaking is minimal once the throttle is at full level. The support system was well designed for our needs. The skirt is strongly attached and air-tight. Although the skirt has folds to ensure proper length along the deck, the profile is nearly level and the gap fix allows the craft to hover higher. The skirt fills well when inflated from the propeller indicating that the splitter functions properly and the contours of the skirt were cut and attached well. The clearance gap between the propeller and the duct was significantly reduced since the air that previously escaped the wrong way now follows the correct path. The rudders divert the thrust air as can be felt when driving and steering along a downwards slope. Better maneuverability can be obtained by shifting the driver’s weight across the deck to re-distribute the air in the pressurized cushion. The cantilevered design for the splitter is held rigidly with fiberglass within the duct and resists the forces from the propeller air well with small vibrations.

Discussion

Although the hovercraft achieved our basic goals for movement, we are limited in our capabilities. This is due to several inefficiencies and problems in the construction and design of the craft. The most significant problem was likely the misplacement of the height of the splitter within the duct. As can be seen by the capability to support over 300 lb. with the engine at full throttle, we overestimated the necessary amount of power from the propeller and engine to divert to lift. This is most likely attributable to the testing method used to find a proper height for the splitter. The height was found by raising and lowering a temporary L-joint within the duct that was attached to the Unistrut frame attached to the back duct support. The temporary structure vibrated much more than the final, fiberglassed air box and allowed for leakage around the borders. The leakages reduced the amount of air diverted into the cushion while the vibrations in the temporary air box were transmitted to the propeller, reducing the efficiency of the propeller. The propeller and engine both ran much more smoothly when the final air box was installed. A more rigid and well-sealed testing method for the air box would have reduced these inefficiencies since the final air box cannot be changed since it must be fiberglassed in place. This unnecessarily high height for the splitter reduces the volume of thrust available, eliminating the possibilities to overcome grass or uphill slopes. Another inefficiency stems from the large clearance between the propeller and the duct. Although this was minimized by introducing the hose to block the gap, the obstruction adds more losses along the passage of air flow. A smaller diameter duct would act to minimize this gap and also to reduce the weight and amount of material used. A rigid engine mount reduces the vibrations of the propeller, making the 2-inch clearance unnecessary. A third problem with our current design is the sharp bend necessary to move the air from the propeller into the air cushion. Guide vanes inserted within the duct would reduce the losses associated with this nearly 90^0 bend.

We can also make alternate design changes. A more powerful engine would provide more energy for both lift and thrust. This would require re-considering the design of the engine mount because a much larger engine would require a metal support. A larger propeller correctly matched to the engine would increase the air flow, achieving the same results as a more powerful engine. This would also require a larger duct and a re-examination of alignment issues. An increase in the size of the deck would allow for less power required for hovering since the pressure in the cushion would decrease for the same payload capacity. However, this involves using more material for the deck and skirt while adding additional weight to the craft.

Acknowledgments

We would sincerely like to thank everyone who helped us complete our senior engineering project.

Specifically, we thank:

- Prof. Macken for advising the project
- Grant Smith for always thinking ahead
- Prof. Orthlieb for his inestimable wisdom and limitless experience
- Julia Luongo for her effervescence
- Alex Bell and Andres Pacheco for help testing the hovercraft
- David Bober and Roby Velez for always having good ideas
- James Beall and Jesse Bertrand for an E14 report on rudder design
- Philadelphia Chapter of ASME for granting our student proposal

Appendix A (Raw Parts Listing)

Part	**Quantity**	**Total Cost ($)**
4’x8’x1/4’’ Plywood	4	145.44
4’x8’x1/2’’ Plywood	1	43.41
4’x8’x3/4’’ Plywood	1	56.80
4’x8’x2’’ Blue Foam	1	44.80
5’x12’x1/16’’ Aluminum	1	85.35
36’’ Finished Propeller	1	136.00
Propeller Back Up Plate	1	17.50
4.5’’ Taper Lock Al Hub	1	50.00
12 yards Fiberglass Cloth	1	47.40
HH-66 Vinyl Cement	2	30.00
5.5 yards x 61’’ PVC Coated Polyester	1	54.73
10 Hp Tecumseh Engine	1	400.00
Fiberglass Resin and Hardener	2 Gallons	140.00
Total		**1251.43**

Appendix B (Blueprints of Parts)

Duct and Air Box

Front View

Bottom View

Side View

Deck

Engine Mount

Appendix C (E14 Report)