Redesign of REV Jet Ski stability and handling

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Abstract / Project Scope

The UWA REV (renewable energy vehicle) project dedicates in building zero emission vehicles that are powered by electricity from renewable sources. There has been numerous successful projects such as the electric Lotus Elise and the electric Hyundai Getz that were completed by REV. With its first prototype debut in 2015, the REV Jet Ski (REVski) project aims to convert a conventional petrol engine Jet Ski into an electrical one, while retaining the Jet Ski's normal functions. The purpose of this project is to promote the reduction of fossil fuel and noise pollution as a personal water craft (PWC), as well as to ensure the safety for the rider or the environment is not compromised by the conversion. As UWA is the first university in Australia that looks into this electrical conversion, and since there is a big market for water sports and tourism in Australia, it is highly possible that the REVski could be commercialised.

However, during the initial on-water test in 2015, it was discovered that the REVski was very 'front-heavy', which means the longitudinal centre of gravity was far too forward. This had led to the Jet Ski to dip into the water during deceleration, making the Jet Ski very unsafe to operate on. Moreover, the excessive weight distribution at the front made the Jet Ski very difficult to handle. The above two problems are definitely the disadvantages when considering this project for commercialisation, and to overcome these, the author has conducted a series of design and testing to improve the REVski's stability and handling, which is the focus of this thesis.

Acknowledgement

I would like to thank my project supervisor, Professor Thomas Bräunl for guiding us – a group of mechanical engineering students throughout this electrical oriented project. I have learnt a lot about electrical vehicles through this project and the interdisciplinary experience will definitely help me along the way of being an engineer.

I would also like to thank Michael Stott, a former REVski member who has taken his time and shared his knowledge. Thanks to Marcus Pham for all his help. And a big thanks to the REVski team for their work, dedication and friendship.

At last, I would like to thank my parents, my two beautiful children, and especially my wife. I could not have done this without you.

Nomenclature

Aft	Toward the stern
CAD	Computer aided design
CB	Centre of buoyancy
CG	Centre of gravity
Draft	Distance between keel and the waterline
Forward	Toward the bow
GM	Metacentric height
GZ	Righting arm
KB	Distance between keel and centre of buoyancy
KG	Distance between keel and centre of gravity
KM	Distance between keel and metacentre
LKB	Longitudinal centre of buoyancy
LKG	Longitudinal centre of gravity
LM	Longitudinal metacentre
PWC	Personal Watercraft
Stern	Back end of a watercraft
VKG	Vertical centre of gravity

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1. Introduction

Internal combustion engine has been used in transportation since 1880, and has been deemed one of the major contributors for global warming. Nowadays, with the increased awareness of greenhouse gas emission and global warming, more and more people favour renewable energy driven transport to reduce the damage caused by carbon emission. The UWA REV project has been converting electric cars from normal road cars since 2008, and has made several positive outcomes such as the electric Lotus and the electric Hyundai Getz. Since there is a big market in Australia for water sports and tourism, it seems feasible to convert a conventional Jet Ski into an electric one, removing the two negatives – noise and pollution.

The REVski project started in 2013, and had its testing debut in 2015 which made several headlines in the media. The REVski is based on a 2008 Sea Doo GTI130 Jet Ski, retrofitted with a 3-phase induction electric motor, 240 10Ah lithium iron phosphate batteries, a Curtis 1238 motor controller and other various electrical components to ensure its safety and performance.

The 2015 on-water test has proven that an electric Jet Ski is feasible and safe to operate, and it has a lot of potential as a personal watercraft. However, a few aspects of the REVski was observed to be in need of improvement. One of those is the redistribution of weight of the components in order to improve the handling the REVski, making it feel and handle more like a conventional Jet Ski. There have been previous studies on the transverse stability of the REVski, and it has been proven through the first testing in 2015. However, the longitudinal stability was somehow neglected, which is one of the reasons that the handling was very poor during the initial on-water test.

Although the ultimate objective is to determine the optimal centre of gravity (CG) of the REVski to match the handling of its petrol engine counterpart, the CG can only be estimated with the help of computer aided software prior to re-distributing component locations. Since there are numerous electrical components with different sizes and weight, different gauge wirings connecting to them and some added components and cables by other project members, it is extremely difficult to account for each of them to acquire a very high accuracy of the CG location. Therefore, all calculations and computer models are only close estimates until a proper on-water test is conducted. Although it is the intention by the author that to conduct the on-water test to prove the design, due to time constraints and project delays, the on-water testings of REVski carried out on 8th and 9th of Novermebr 2017 are not as comprehensive as desired at the time of the editing of this report.

Figure 1 REVski media coverage screenshot and rough locations of forces. (University of Western Australia, 2015)

2. Problem Identification

It was discovered in the 2015 on-water test that the REVski was very front-heavy. The rider had to sit very far behind on the Jet Ski – away from the driver's seat, in order to counter-balance the Jet Ski's tendency of bowing into the water. As stated before, the longitudinal stability was overlooked, thus there is no data or resource available to determine the longitudinal centre of gravity (LKG) for the previous design. ***Figure 1*** is a screenshot from the media video on the day of 2015 testing, and it is obvious that the rider takes some effort to keep the Jet Ski level in the water.

It can be seen in ***Figure 1*** that the REVski is operating at relatively level state. For a vessel to float levelly in the water on the longitudinal plane, the centre of buoyancy (CB) needs to act at the physical centre of the vessel as indicated by the blue arrow. The fact that the rider siting at the back of the Jet Ski (red arrow) provides a counter clockwise moment with the buoyancy force, which means there is an equal but opposite clockwise moment created by the gravity force of the Jet Ski (green arrow) at the front to keep the vessel level. Thus, it is determined that the LKG of the REVski is too much at the front.

As a result, the front-heavy LKG causes the REVski to bow severely into the water during deceleration, which is also known as pitching. On a reliability perspective, 'the aft draught must be large enough to ensure sufficient propeller submergence and avoid cavitation.' (Biran & López-Pulido, 2014, p. 172) Cavitation could result in loss of power and potential damage of propeller. On a rider experience perspective, as shown ***Figure 1***, the rider's riding posture provides neither comfort nor safety, which is a drawback from potentially being commercialised in the future.

Thus, the solution to this problem is to alter the position of the major components, so that the LKG of the REVski can be as close to the driver and the longitudinal centre of buoyancy LKB as possible to provide a stable ride, improve its manoeuvrability and enhance its performance. Due to the relocation of the battery packs, the heavy load that they assert on the other components could damage them. Therefore, the battery cell configuration, battery mounting system as well as the mounting location need to be redesigned to ensure the security of other electrical and mechanical systems.

3. Literature Review

3.1 Principle of Floatation

Archimede’s Principle states that a body immersed in a fluid experiences an upthrust equal to the weight of the fluid displaced, and this is fundamental to the equilibrium of a body floating in still water. (Molland, 2008) The downward force that the floating body generates is simply its weight *mg*, which is the product of mass of body *m* and gravity g. The weight is only acting on a certain spot which is called the centre of gravity CG. The centre of buoyancy CB, on the other hand, is a point where a vessel’s buoyancy force is concentrated, and the buoyancy force is always acting upwards. CB is not a set point, but it rather varies due to the shape of the vessel immersed in the water. Because of the equilibrium condition, the buoyancy force generated by displacement *v* of fluid should be of the same magnitude but opposite direction with the weight of the body, which means $mg = \rho g v$, simplified as $m = \rho v$, where ρ is the density of the fluid. Although the body can be of any shape, it can be traced down to the root that the force acting on the centre of gravity CG of the body should be equal and opposite to the force acting on the centre of gravity of the fluid that is displaced, which is also called centre of buoyancy CB, as depicted in ***Figure 2***.

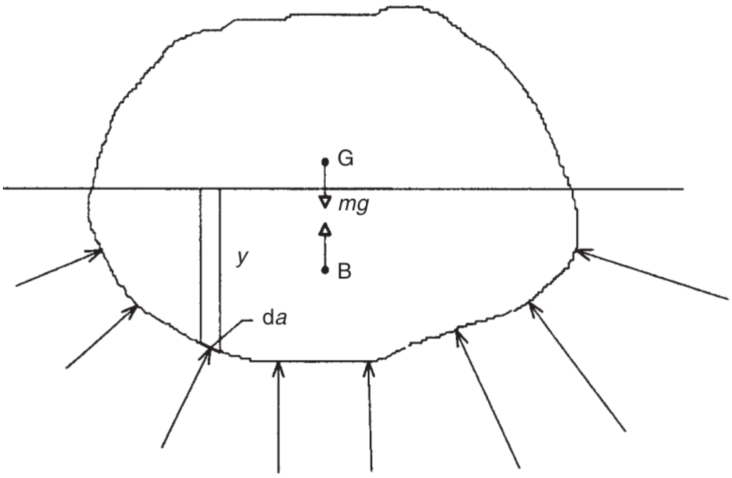

Figure 2 A floating body. Note: From The Maritime Engineering Reference Book - A Guide to Ship Design, Construction and Operation p.77 (Molland, 2008, p. 77)

3.2 Vessel Longitudinal Stability

It is vital to position weights on a ship correctly, as their disposition have direct impact on the centre of gravity CG. Whether CG is higher or lower determines if it increases or diminishes the stability. (Morgan & Creuze, 1833) In order to improve the handling of the REVski by minimising the pitching, through observations, it seems clear that the distance ofC of the front half of the REVski must be identical to the distance of CG of the rear half in relation to the CG of the whole REVski. Also the sum of moments of inertia of the front half of the REVski should equal to that of the rear half. (Henwood, 1833)

There are two major planes in the geometry of a vessel, the middle line plane which is in most ships the only plane of symmetry, and the transverse plane which is perpendicular to the middle line plane and spans from side to side. (see ***Figure 3***.) The plane that is at right angles to both the middle line plane and transverse plane is called water plane, however, it is not necessarily in the water. (Rawson & Tupper, 2001)

Stability is the ability of a vessel to return to a previous position. Positive stability would then be to return to upright and negative stability would be to overturn. Stability in its most basic form is the relationship between the centre of all floatation in your hull (or CB) and the centre of all weight (vertical centre of gravity, or VKG). (Bray, n.d.) In other words, CB and VKG are the two major contributors to the stability of a vessel.

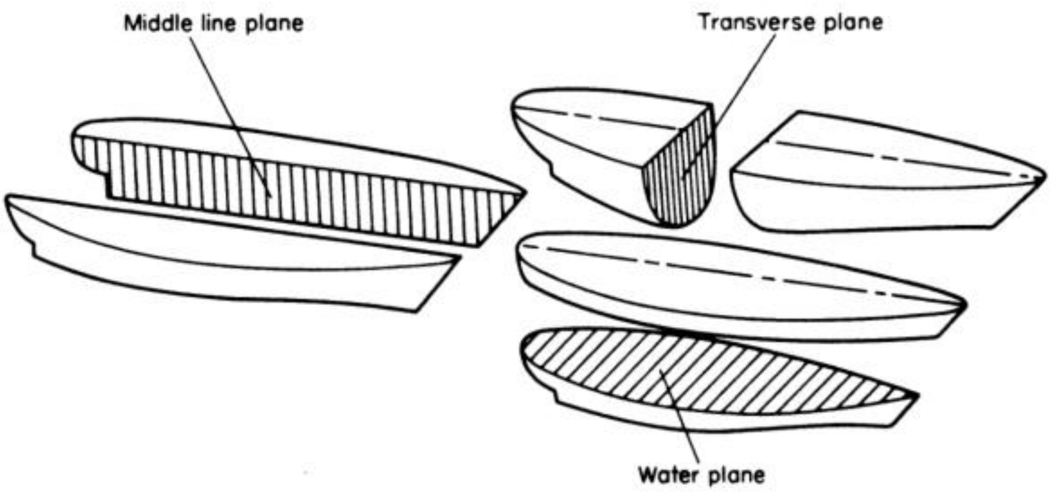

Figure 3 Planes of a watercraft. Note: From Basic Ship Theory p.8 (Rawson & Tupper, 2001, p. 8)

Longitudinal stability shares the same principle of that for transverse stability, only in this case the distance between KM and the longitudinal metacentre LM plays the determining role. The distance between the centre of buoyancy CB and LM will be dependent on the second moment of area of the water plane. (Molland, 2008)

As depicted in ***Figure 4***, x is the distance between the CG and amidships when the vessel is floating in equilibrium at the waterline W_0L_0. The centre of buoyancy B_0

must be directly beneath CG. Assuming a new waterline W_1L_1 was introduced, the new centre of buoyancy will be at B_1 and the distance between KG and amidships is y. Let *t* be the trim, then when the ship was at W_0L_0,

$\Delta(y-x) = t \times (moment\ to\ cause\ unit\ trim)$ and

$x = y - \frac{t \times MCT}{\Delta}$ where MCT is the moment to change trim and Δ is the corresponding water displacement.

As a result, the moment of inertia increases as the distance from the weights from the transverse plane in which CG locates, which results in a slower and deeper pitching. Deep pitching not only reduces a vessel's forward velocity, but also causes discomfort to its passengers because of the waves breaking over it, so it is considered a great disadvantage for the performance of a vessel and thus needs to be eliminated as much as possible. (Morgan & Creuze, 1833)

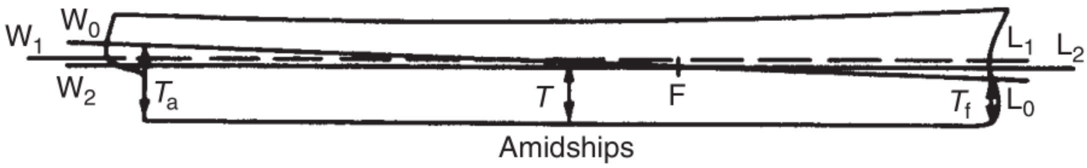

Figure 3.13

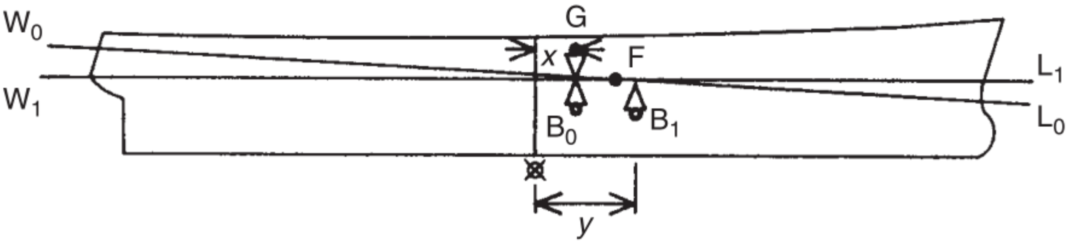

Figure 4 Longitudinal position of centre of gravity. Note: From The Maritime Engineering Reference Book - A Guide to Ship Design, Construction and Operation p.85 (Molland, 2008, p. 85)

3.3 Standards

The ultimate purpose of setting ship's stability standards is the make sure that vessels are operated safely 'without fatal capsizing casualties during their service lives' (Belenky & B.Sevastianov, 2007). Therefore, it is vital that various standards to be referred to when conducting designs on the REVski, in order to ensure the operator's safety.

3.3.1 ISO 13590:2003

According to this standard, the stability of a PWC in the static floating condition is limited. 'When a personal watercraft is floating upside-down, the operator shall be able to return the personal watercraft to the upright position, and go on board again.'

(International Organization of Standardization, 2003, p. 19) Although it does not specify the physical requirements of a PWC, it does indicate that the PWC should be able to return to the upright position with the help of the operator.

3.3.2 ISO 12217-3:2002

This standard aims to evaluate the stability and buoyancy of intact boats. Some of the assessment described in this standard will be used when assessing the stability and buoyancy of the REVski, ensuring that it is safe to ride on and easy to handle. The tests that this project will adopt are: offset-load test, level flotation test, basic flotation test and capsize-recovery test in order to comply with ISO 13590:2003. (International Organization of Standardization, 2002)

3.3.3 AS 1799.1—2009

The Australian Standard 1799 provides method for calculation of maximum load capacity, as well as determination of required volume of flotation material and assessment of level flotation, which are all essential to the stability of the REVski. It also provides guidelines for heeling test which ensures the transverse stability of the vessel. (Standards Australia, 2009)

3.3.4 National Standard for Commercial Vessels Section 6 Subsection 6C

This subsection of NSCV provides specific requirement for the stability test to determine a vessel's stability characteristic, as well as stability safety information for personnel operating the vessel. The inclining test mentioned in this standard was used as a means of acquiring stability data for the REVski.

3.4 Previous Work/study

A past thesis written by a former REVski team member has provided numerous useful information about the past work that has been done to the REVski. It has discussed the mathematical relationships of CG, CB and metacentre M, and has suggested that for the REVski, 'it may be desired to have large GM to make the watercraft stiffer and harder to flip over when traveling at a fast speed.' (Low, 2015, p. 12) The article provides valuable information regarding reverse engineering of the hull, inclining experiment and other tests to enhance transverse stability of the REVski. However, this article has neglected the address the longitudinal stability of the vessel, and this provides an opportunity for the research in this project. The method covered in Low's article could be considered as a reference when conducting longitudinal stability enhancement in this project.

4. Methodology

4.1 Disassembling of Major Components

The major contributor of the front-forward LKG of the REVski are the components with the most weight, being the batteries, battery brackets, motor, motor controller box and the contactor box. There are two I-beams supporting the battery packs, as well as eight battery clamps made of laminated wood, which also affect the LKG.

The above components are removed from the REVski as they are the ones that need to be relocated for the weight re-distribution. The AC motor is the only exception, because it must use the existing engine mounts so that it does not affect the seaworthiness of the REVski. Another reason for a component disassembly is that since the previous build of the REVski did not have an effective battery management system, a big portion of the batteries sustained irreversible damage and could not perform as desired. They need to be taken out to be replaced, thus all major components need to be uninstalled to make room for the exit of battery packs.

Each part is individually weighed for future calculation of centre of gravity and how this is achieved will be covered later in this report.

4.2 Modelling of REVski LKG

Due to the physical constraints of the REVski hull and the cost of parts involved, a trial-and-error approach is less preferable. It is more practical to calculate the centre of gravity and the relevant properties as accurate as possible before physically commencing the assembly and testing the design in the water.

To achieve this, computer aided design is utilised extensively in the early stage of the designing phase. The main software that is used in this project is Solidworks, which is selected due to availability and the author's familiarisation with it.

4.2.1 Reverse Engineering of Hull Interior

The inside of the hull is reverse engineered using Solidworks in 3D. This step involves data capture, pre-processing, segmentation and surface fitting and CAD model creation (T. Varady, 1997). First, reference points at aft, rear engine mount, front engine mount, rear battery support bracket, front support bracket and forward all taken from the interior of the hull, and their relative distances are measured from inside of the REVski (data capture). The reference points with their relative distances are then converted as set points in the Solidworks (pre-processing). At each point, a reference plane is created so that it is easier to create a 3D model of the hull interior. A sheet metal sweep is conducted in the Solidworks model to represent the interior surface of the hull, in order to make sure that the moved components do not come in contact with the surface so that it eliminates the chances of components rubbing. Also because of symmetry, only half of the model is swept so that the longitudinal setup is clearly visible. After the 3D model is created (segmentation, CAD model creation) as seen in ***Figure 5***, different weight distributions could be tried for the optimal result.

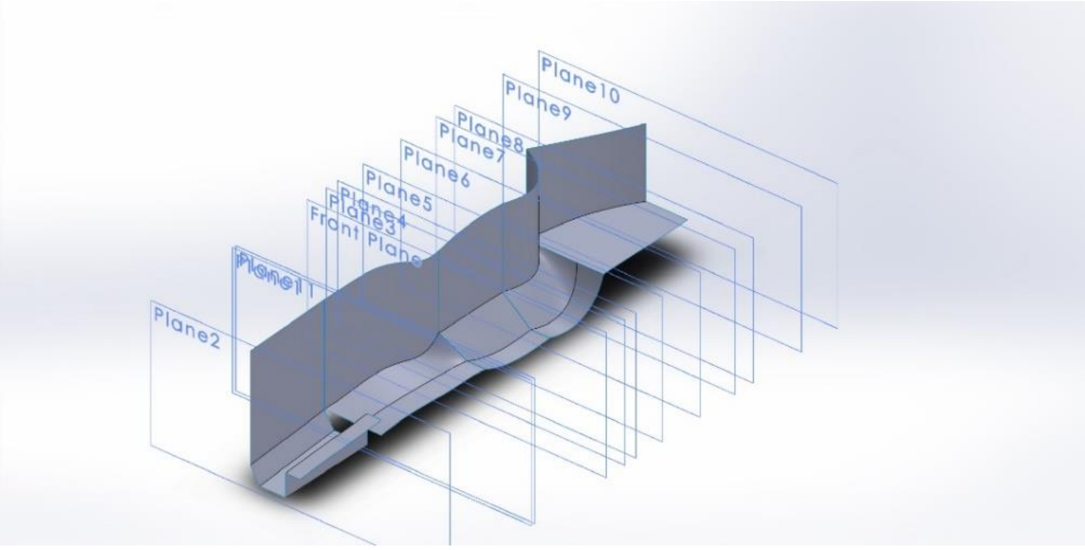

Figure 5 CAD model of hull interior surface.

4.2.2 Component Modelling

In order to get the LKG as accurate as possible, each major weight contributing component is weighed using a body scale (***Table 1***). The total weight of the components that are taken out of the REVski is 421.2 *kg*.

The dimensions of the components such as the motor controller box, battery pack tube, contactor box, are also measured. Each component is assumed as a body with uniform density, which has a KG at its own geometric centre. The above components are modelled with the proper dimensions according to the measurement, and the individual density of each component are then assigned to their Solidworks part as mass properties. Once the dimensions, density of all major components are assigned, the LKG can be easily calculated by Solidworks.

Table 1 Measured mass for each component

Component	Measured mass	Reference mass	Mass per component (kg)
Motor control box	15.64	0	15.64
Contactor box	4.74	0	4.74
PVC casing	83.6	74.1	9.5
Battery end cap	75	74.1	0.9
Battery (64) + 1 end cap	99.3	0	98.4
Metal plate (motor ctrl support)	78.1	74.1	4
Total weight			421.2

4.2.3 Rearrangement of Components

The critical parts are arranged as assemblies in various physical configurations to determine which setup could alter the centre of gravity of the REVski to be as close to the desired region as possible, without the team performing hands-on work to the REVski. To combine two CGs of different components into one for the assembly, consider a straight line connecting the two CGs. Then find a point on the line where the product of mass and distance for both sides are equal. It is clear that hand calculation of the CG of a multiple-component assembly is time consuming and can introduce errors very easily, thus Solidworks is an excellent tool to eliminate the disadvantages of hand calculation.

By altering the component configurations, not only can the centre of gravity of the REVski be found without hand calculation, but also the feasibility of physical configuration and parts clearance can be visually inspected before building the vessel.

Various positions of the batteries are considered first, as they are the heaviest components aside from the motor. Also, different battery pack sizes are considered as shown in ***Figure 6***. The original design had 4 battery packs with 2 containing 8 cells in series (8s) and 2 containing 7 cells in series (7s), totalling 30 cells in series. Different battery pack configurations, such as 2 packs with 7s and 4 packs with 4s, and 3 packs with 8s and 2 packs with 3s. The configurations can be found in the figures below. As it can be seen, the LKG changes with different locations of the components. In each iteration, the LKG moves a little to the back, which is where the LKG is preferred.

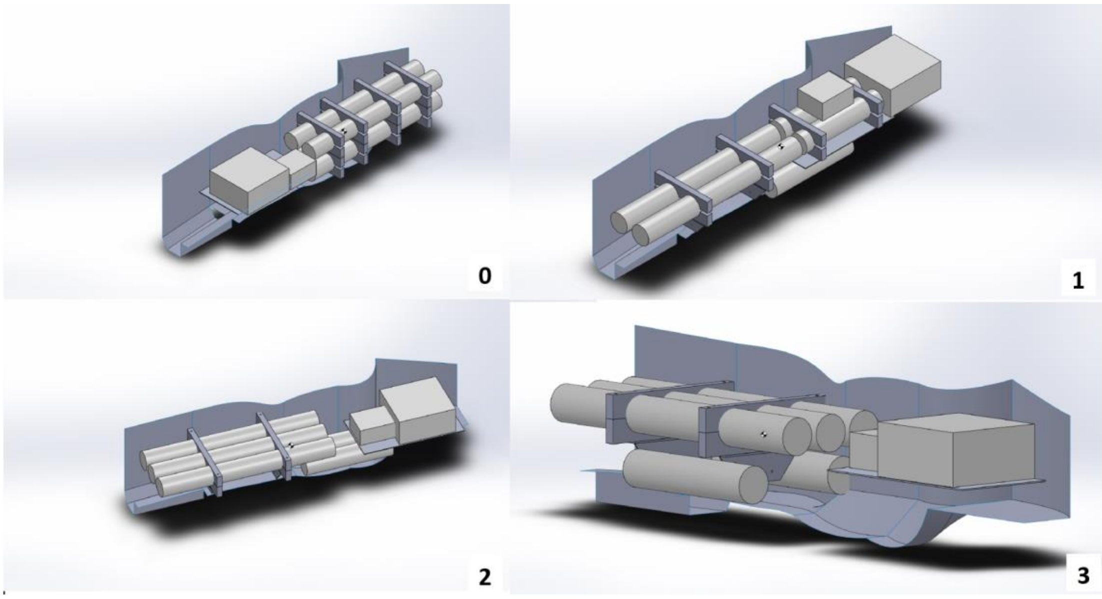

Figure 6 Battery pack designs. V0: Original design. V1,V2,V3: different design iterations.

In the CAD model, a plane at which the front motor mount is located is selected to be the origin plane, which is the target plane for which the LKG should be as close as possible to. The origin plane is where the midship is, as proven by the physical measurement of the Jet Ski. As it can be seen from ***Figure 7***, the LKG from original design (V0) and design iteration V1 and V2 are all in front of the origin plane, whilst design iteration 3 displays a negative distance which indicates the design could be back heavy. Detailed data are shown in ***Table 2***.

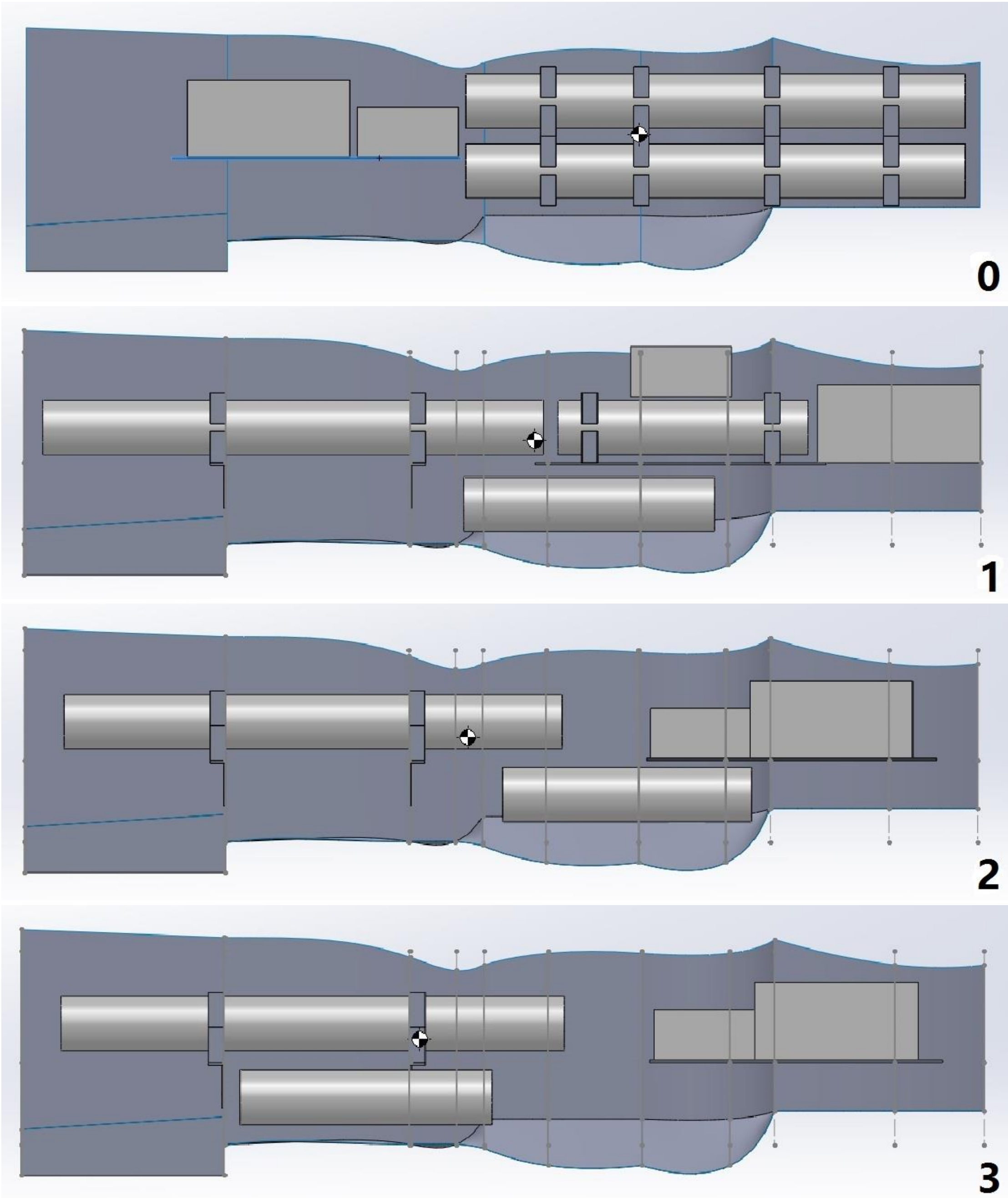

Figure 7 Component configurations. V0: Original design. V1,V2,V3: Different design iterations.

Table 2 LKG location of different designs.

Design iteration	LKG wrt. Origin (mm)
V0	471.28
V1	202.72
V2	33.94
V3	-94.71

4.2.4 Achieving the Overall LKG

With the above parts removed, a weighing of the left-over REVski is conducted to find its existing centre of gravity, so that the 3D modelled CG and the CG of the hull and motor can be added together to achieve a final and overall centre of gravity of the completely assembled REVski. In this way, the longitudinal CG can be discovered, and the team can discuss over the improvement of the handling with regards to LKG.

The weight of the REVski hull was weighed using an industrial scale, and the measured mass is to be 326 *kg*. Then the Jet Ski was lifted by specially designed lifting hooks, so that the LKG of the hull can be determined. Coincidentally, the LKG of the hull lies at the origin of the CAD model, which means the LKG of the hull can be considered as the origin.

Under the assumption that the vertical element of the LKG are the same, then the total LKG of the REVski can be calculated by a simple equation. We assign the mass of the hull to be *M1* and mass of the rest of the components that are disassembled to be *M2*. Whilst *M1* is the origin, the moment generated by *M2* at a distance d about the origin should be $M2 \times d$, which should equal the moment generated by the whole weight of the REVski about the origin, being $(M1+M2) \times n$.

Rearranging the equation, we get $n = \frac{M1}{M1+M2} d$, which is the distance between the overall LKG and the origin. Referring to ***Table 1***, we know that *M1=412.2 kg*. And from the weighing of the hull we know *M2=326 kg*. *d* is the 3D model LKG with respect to the origin has shown in ***Table 2***, and the LKG of the REVski with respect to the origin n can be easily calculate with results shown in the table below.

Table 3 Total LKG with respect to origin.

Design iteration	LKG wrt. Origin (mm)	Total LKG n wrt. Orignin (mm)
Original	471.28	265.22
V1	202.72	114.08
V2	33.94	19.10
V3	-94.71	-53.30

It can be clearly seen that the original LKG is very far from the origin (midship), whilst LKG of design V2 and V3 are much closer to the origin. V2 was initially selected to be the preferred design as its LKG is the closest to the midship. However, after careful consideration of the manufacturing process, the team has found that it is very difficult to securely place the two small battery packs at the bottom of the hull. It is suggested by a former REVski team member Michael Stott to use foam as a cushion between the hull bottom and the battery packs, but even so there are no attachment points for anything that could hold down the battery packs. The discussed section of the hull is of smooth surfaces with no existing mounting points, which means the battery packs cannot be held down securely without significant modification, and any drilling of the hull will void the seaworthiness.

As a result, a compromise is made through team discussion to use design V3 as the final solution, due to its easier manufacturing process. Although the LKG is further away from the origin and it is back-heavy, the two battery packs can be easily secured by implementation of a new bracket, which can be bolted onto the existing motor mount. It is initially thought that the top three long battery packs could be moved slightly forward to compensate the back-heavy LKG, however after the build it has seemed to be not feasible, as the reverse mechanism is in the way of one of the three battery packs, making it impossible to move. The other two long packs are moveable, however, only moving the two could introduce an imbalance of the weight distribution, which significantly changes the stability of the Jet Ski. As a result, the overall design has ended up with a back-heavy LKG, with the distance of the LKG being 53.30mm by the aft.

5. Final Design and Testing

5.1 Final Design

As discussed in the last paragraph in 4.2.4, the final design is selected to be design iteration V3 (***Figure 8***). This design consists of three 1.3m long battery packs each contains 8 battery cells, and two 0.6m short battery packs each containing 3. The long battery packs will be secured by two newly designed bracket made of aluminium, which are attached on top of the existing motor mounting plates. The short packs are mounted by separate brackets/clamps that suspend the battery packs. The PVC tubes for the short packs are made from halving one of the original long tube, and an extra pair of end caps, as well as battery leads will be made as the total battery packs will increase from 4 to 5.

The motor controller box, contactor box and all other electronics are relocated to the front of the Jet Ski, under the front hatch to make the components more accessible. The motor controller box lid was modified with its hinges cut off to enable its opening in the confined space under the front hatch, and it is mounted on a plate which is secured by 4 screws into the existing wooden brackets that were previously used as battery brackets. A special supporting platform is fabricated for the contactor box to sit on. All electric cables and wires that connects to components at the back will be extended to the front due to the relocation of motor controller box and contactor box.

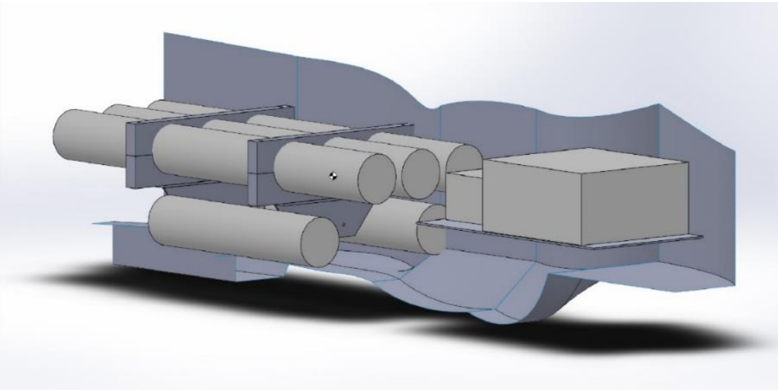

Figure 8 Final weight distribution design.

By comparing the original weight distribution with the new design, it can be seen in Figure 9 that the LKG has shifted to the back of the Jet Ski for a large amount.

The next stage would be to re-assemble parts according to the proposed design, and conduct on-water tests to find out the real KG and KB.

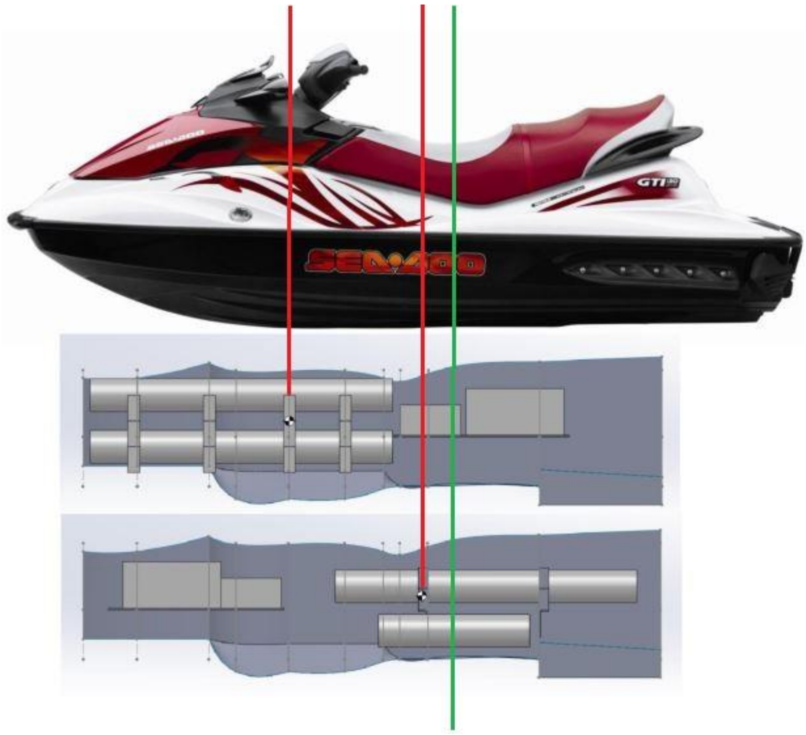

Figure 9 LKG comparison. Note: Top image retrieved from NADA Guides Boat Pricing (NADA Guides, n.d.)

5.2 On-water test

The inclining experiment is a common measure to determine the stability of a vessel. Although is more widely used for newly constructed ships greater than 24m in length (Wikipedia, n.d.), it is still applicable in this project in determining the Jet Ski's stability. Through this test, the metacentric height GM can be determined, which is crucial to a ship's stability.

Draft marks at Forward, Aft and Midship are made clearly visible on the sides of the REVski as shown in ***Figure 9***. Two 1.25 *kg* dumbbell weights are used as standard test weight, which means the test weight is 2.5 *kg* each. A smart phone app Advanced Bubble Level was used to check the change in angular degrees when test weights are moved. The phone will be securely attached to the REVski by taping it down using masking tape.

Figure 10 Draft marks on the REVski.

The procedure of the inclining test is as follows:

1. Read draft marks at bow, stern and midships on both sides.
2. Move weights in the order as shown in Figure 10. Take draft readings after each movement.

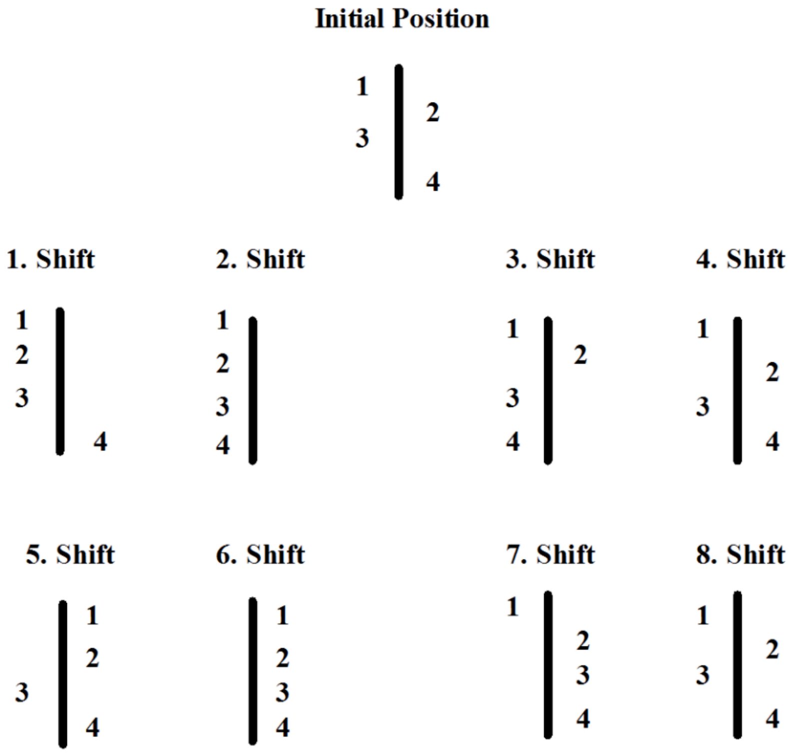

Figure 11 Inclining test weight shifting order. (Australian Transport Council, 2010)

3. While taking draft readings, angles of inclination are also taken down from the phone app. The phone app interface can be seen in the figure below.

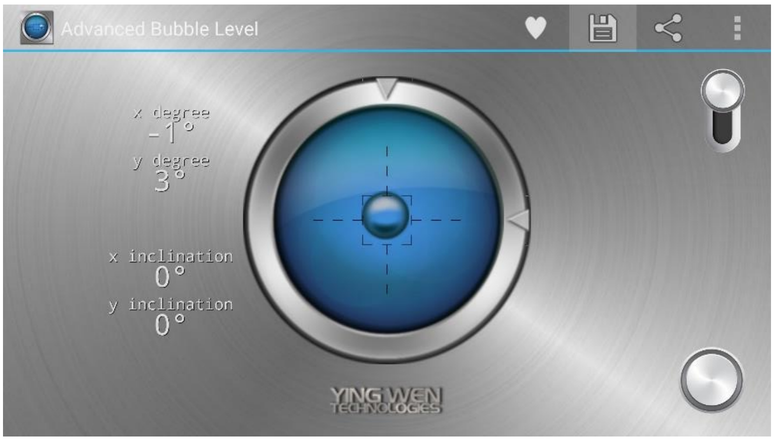

Figure 12 Phone app used in inclining test. Actual data shown in figure is irrelavent to this report.

To calculate GM, the following equation is used

$$GM = \frac{w \cdot d}{W \cdot tan\theta}$$

where

w = weight shifted

d = distance of weight shifted

W = displacement – from hydrostatic chart

φ = angle of inclination – from reading of phone app

The calculated GM are shown in the table below.

Table 4 Test data and calculated GM value.

Test #	θ_X	Tan	wd/Δ(m)	GM(m)
0	0	0	0.0064	N/A
1	1.9	-2.9271	-0.8156	0.2786
2	4.1	1.423526	0.3579	0.2514
3	6.25	-0.0332	-0.0063	0.1898
4	0	0	0.0064	N/A
5	-6.7	-0.44276	-0.0814	0.1838
6	-4.4	-3.09632	-0.8179	0.2642
7	-2.1	1.709847	0.6390	0.3737
8	0.1	0.100335	0.0065	N/A

It is the author's intention to conduct a similar test for the longitudinal stability test using the same method, however, due to the difficulty of attaching weights to the Jet

Ski on the longitudinal plane and the time constraint that the author faced during on-water testing, the proposed longitudinal test was not successfully conducted.

6. Results and Discussion

The experiment data wd/Δ and $tan(\theta_X)$ are then plotted in the following graph. When θ_X is in radians, the slope of the curve and the linear fitting is the magnitude of GM. the linear regression analysis is used to fit the measured points. It can be seen that the line of best fit goes through most of the data points, which indicates a good stability that is achieved by the new weight distribution.

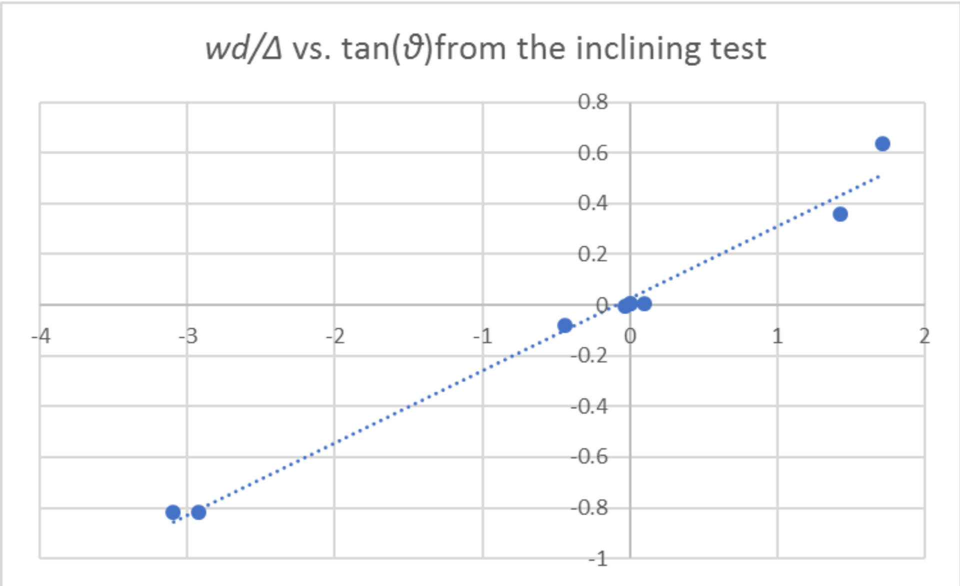

Figure 13 Line of best fit for inclining test data

The end result for the LKG of the Jet Ski seems to be somehow over-adjusted. From the picture below, it can be seen that the REVski is now back heavy.

Figure 14 Back heavy LKG as seen in water.

Moreover, the fact that the LKG of the new weight distribution does not fit as designed, is partly due to the new battery configuration. The reverse mechanism was not taken into account when configuring the weight distribution, so that at the time of assembling the battery packs into the hull, it was discovered that the longer battery packs cannot move any more forward as the reverse cable is in the way, resulting in a slightly backward LKG. The locations of the shorter battery packs are also shifted too much backwards due to the physical constraints of the new bracket, which only allows a certain position for the packs and is not adjustable. As a result, the actual LKG of the REVski is much more further back than it was designed.

Based on the test ride feedback from Professor Thomas Bräunl who is the only one in the team that has ridden the 2015 model, the handling resulted from the new weight distribution is 'ten times better'. From the test ride experience by the author, the back-heavy can be felt especially when turning at speed, as the back of the REVski tends to oversteer. But the symptom of dipping into water when braking, which was the major safety concern for the 2015 prototype, could not be experienced thanks to the shifted LKG.

7. Resource Restrictions

With the tight budget that the team has, it is advised not to spend on unnecessary trials. However, there are a few parts that have to be purchased in order for the project to proceed. Due to the lack of battery management systems (BMS), some of the batteries were either physically damaged/leak acid, or exhibit signs of failures in performance. There have been 21 batteries out of 240 that have failed, and they have to be replaced by new ones. Each battery is at a retail price of $25, so there has already been $525 spent on batteries alone.

In terms of this project, making of new battery container brackets and battery containers is another area that requires financial expenditure. Because of the re-distribution of the battery containers, existing brackets and containers cannot be reused due to their physical constraints. Thus, the new designs need to be manufactured by the mechanical workshop of UWA, which charges at a labour rate of 75/hr. It is estimated that the total labour should be within 3 hours, however there may be more expenditure required for materials as the project continues.

On the other side, the team is privileged to receive support and sponsorship from past students and the industry.

8. Conclusion and Future Work

Overall, this project has made satisfactory results, under the constraint of budget and time.

The result of this project demonstrates that computer aided software provides accuracy in pre-determining the feasibility of a design, however, the accuracy depends on the capability of the person who utilises the software. There are various aspects of the design that are assumed to be negligible or simply not put in due to technical difficulty, such as various electrical components and cables, the Jet Ski hull and the AC motor. The more models that are input into the software, the high accuracy it yields. Thus, assuming a parameter or input as negligible could end up with significant error. And no matter how accurate the computer design is, it is still essential to conduct a physical test of the design, at least on a scaled model.

3D scanned model could be used in the future when constructing CAD model of the REVski, in order to achieve a higher accuracy of modelling. Although the author was advised of using 3D scan for modelling, under the time constraint, learning to use 3D scan seemed time consuming, thus the plan did not go ahead due to lack of familiarity of the method. However, this could be a future thesis topic for students how would like to join the REVski team.

Also, although engineers choose to adhere design standards when conducting designs, the standards for personal water craft involved in this project did not specify key parameters that were required. Each standard lists different aspects of the PWC, and the lack of unified standard makes it difficult for engineers to design a PWC modification.

The on-water has been conducted in early November, 2017. As the result of the back-heavy LKG and oversteering at corners, a dynamic study of the REVski's handling should be done in the future, because static stability criteria 'are based on technology that does not consider pressures generated by fluid velocity relative to the hull form' (L.Blount & T.Codega, 1992). To reduce the chance of oversteering which could lead to crashing and roll-over, the LKG needs to be shifted forward. As mentioned before, the reverse assembly is in the way for the battery packs to move forward, thus the reverse assembly shall be modified so that it does not interfere the movement of battery packs. Once this is achieved, the LKG of the REVski can be fine-tuned so that it is in an optimal location.

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10. Appendices

On-water Test Data

Test 1					Raw Draft (Port/left) in cm			Raw Draft (Starboard/right) in cm		
Test #	Veight w (kg	stance d (cr	θX	θY	Fwd	Mid	Aft	Fwd	Mid	Aft
0	2.5	75	0	9	20	10	3	19	9	3
1	2.5	75	0.2	9.4	19	10	2	19	9.5	3
2	2.5	75	1	9.3	18	9	2.5	19.5	10	3
3	2.5	75	0.4	9.2	19	9.5	3	19	9.5	2.5
4	2.5	75	0	9	20	10	3	18.5	9	2.5
5	2.5	75	-0.7	9.3	20	10.5	3.5	18	8.5	2
6	2.5	75	-1.2	9.5	20.5	11.5	3.5	18	8	2
7	2.5	75	-0.5	9.4	20	10.5	3	18	8.5	2
8	2.5	75	0	9.3	19.5	10	2.5	18.5	9	2

Test 2					Raw Draft (Port/left) in cm			Raw Draft (Starboard/right) in cm		
Test #	Veight w (kg	stance d (cr	θX	θY	Fwd	Mid	Aft	Fwd	Mid	Aft
0	2.5	75	-0.4	-2	19	10	3	18	9	2.5
1	2.5	75	0.1	-2.1	18.5	9.5	3	18.5	9.5	3
2	2.5	75	0.5	-2.1	18.5	9	2.5	19.5	10	3
3	2.5	75	0.1	-2.1	18.5	9.5	2	18.5	9.5	2
4	2.5	75	-0.6	-2	19	10	2.5	18.5	8.5	2
5	2.5	75	-1.2	-1.9	20	10.5	2.5	18	8	1.5
6	2.5	75	-1.8	-1.7	20	11	3	17.5	7.5	1
7	2.5	75	-1	-1.8	20	10.5	2.5	18	8	1.5
8	2.5	75	-0.7	-2	19.5	10	2.5	18	9	2