Design analysis and modelling of autonomous underwater vehicle (AUV) using CAD

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In the underwater world, an autonomous underwater vehicle (AUV) is created to assist in underwater research. This project presents a design analysis and modelling of AUV using computer aided design (CAD) simulation software, SolidWorks. The scope of this project divided into two parts: (a) AUV design and (b) analysis of battery enclosure stress and strain simulation and flow simulation of 3-blade propeller T100 thrusters. The AUV was designed part by part first and then the assembly of all the parts is carried out. In the simulation stress and fluids were applied on the enclosure box and a thruster, respectively, to observe the reaction of the parts as the frame and pressure hull from Blue ROV design. The result of the stress simulation shows that the enclosure box is very durable and can withstand up to 718.10 Pascal equivalents to 73.2 meter underwater depth. Furthermore, the outcome of flow simulation by using SolidWorks has shown that the maximum velocity of thruster flow is 4.939 m/s, while the acceleration of 5.655 m/s^2 of the AUV is calculated by using thrust force and mass of the AUV.

[**Keywords:** Autonomous underwater vehicle; SolidWorks; Stress simulation; Flow simulation; T100 thruster]

Introduction

Robotic submarine such as unmanned underwater vehicles (UUV) has been designed and developed in the past few decades in various countries. Autonomous underwater vehicle (AUV) is generally battery powered and conveys its own computer to actuate the thrusters for a multiplicity of research seabed platform in underwater technologies[1]. Small size, light weight and high manoeuvrability of AUV are the most important features that can make a small AUV more stable in shallow water to perform given tasks[2]. Figure 1 shows that the design of AUV including the pressure hull, battery enclosure, and configuration of thrusters is very important to ensure the best performance during an underwater operation.

In battery enclosure design as shown in Figure 2, the material used for fabricating must withstand the underwater pressure and stress. Furthermore, in Figure 3 show that T100 thruster[3] is often used in marine robotics, to thrust the AUV and help with the propulsion system. The performance of this thruster depends on the size and propeller design. The 3-blade propeller is designed into T100 thruster to increase the performance of the thruster. Hence, there is a need to test the flow simulation by using SolidWorks.

For this project, SolidWorks was used as a tool to design all the parts of the AUV, as it had been used effectively by other researchers and engineers in the designing of product models. It offers shorter development time, better product design and increasing product performance due to better simulation process[4,8]. The simulation of stress and strain is applied to the battery enclosure and flow simulation is applied to the 3-blade propeller thruster. Basically, this project allows researchers in University Teknikal Malaysia Melaka (UTeM) to gain experience in using a design and simulation software, Solid Works before fabrication process. This is important to know the performance of the project design Furthermore, this project also enhances engineering design skills of the researchers and help them:

- To design the AUV using SolidWorks.
- To analyze the stress and strain simulation by choosing the type of material used in fabrication.
- To analyze the parameter of velocity, force, and acceleration of the liquid under water by using SolidWorks flow simulation software.

Methodology

Figure 4 shows that the flowchart of Solid Works for this AUV design project. There are four main

sections which are designed: Module, part module, assembly module, and a simulation module.

Design Module

The design module allows the user to draw and make sketches of the objects. It is the idea of making an initial drawing for the designers to come out with the ideas for the objects to develop. All the dimensions of the components in AUV should be in a sketch drawing before using SolidWorks design
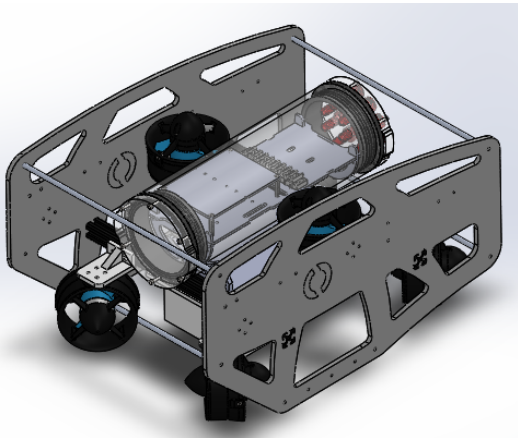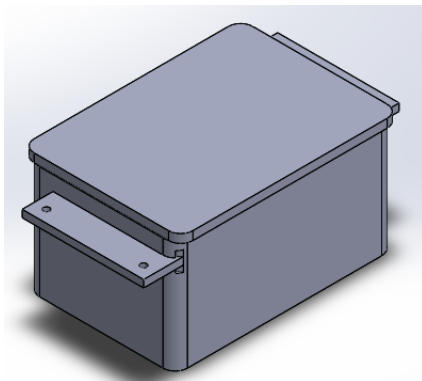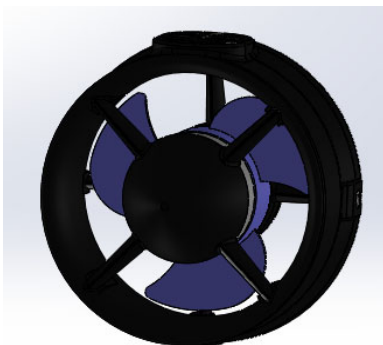

Fig. 1 — Design of AUV

Fig. 2 — Battery Enclosure Box

Fig. 3 — Three Blade Propeller T100 Thruster

software. A savvy measurement instrument in the recent SolidWorks version influences the drawing faster and less demanding.

Part module

The part module of SolidWorks neither drawing of a 3D representation of a single design component. The command toolbar which consists of the sketch, feature, evaluate, etc is used for sketching a geometry including circle, lines, trims, convert entities, mirror entities, etc. and transform it into 3D modeling by using features such as extruded boss, revolved boss, fillets, extruded cut, swept cut, holes, etc.

Assembly module

The purpose of this assembly module is to combine all the individual parts into a complete 3D object. First is to insert the main frame of the object so that it will have a fixed point for the consecutive components. There are two main types of assembly methods: Bottom-up and top-down design. For top-down design, the combination of one or more features of a part can be resized and correct the model parts. The design intent comes from the assembly and moves into the parts module[9].
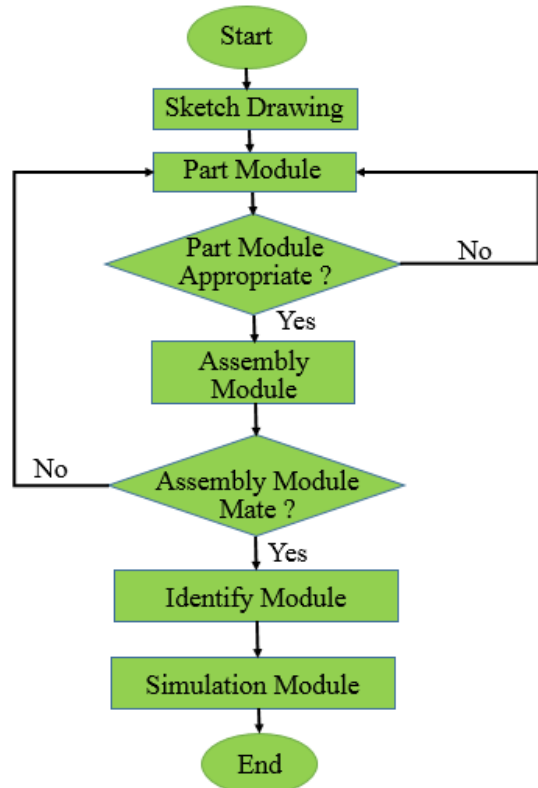

Fig. 4 — Methodology Flowchart

During assembly, the type of mates is important in combining parts as it creates geometric relationships between each component. These are various types of mates to combine the parts such as coincident, parallel, concentric, distance, perpendicular, tangent, etc. Basically, use the least mates to combine the parts to avoid some mating error occur. The assembled parts can be viewed rotationally and exploded by using the tool of motion study as shown in Figures 5, 6 and 7. The motion manager allows forming animations showing motion and sequences during the assembly procedure.

Simulation module

Two types of simulation are used in this project: Stress and strain simulation and flow simulation. The battery enclosure will undergo the underwater pressure test as shown in Figure 8. The stress and strain of the prototype AUV are simulated for the structural analysis in SolidWorks by finite element analysis (FEA) simulation Xpress. For this project, AUV used poly lactic acid (PLA) as the main material for the enclosure box and other fabricated parts[10]. This software is used to analyze the property of safety factors, strain, and stress. The purpose of the analysis is to predict the overall performance of the AUV mechanical construction under the water pressure at the operating depth environment. The pressure acting on the submerged part depends on the depth as shown in Equation (1).

$$P = \rho g h \qquad \qquad ... (1)$$

where
P = Pressure (kN/m^2)
ρ = 1000 (kg/m$^{3)}$
g = 9.81 (m/s^2)
h = Depth (m)
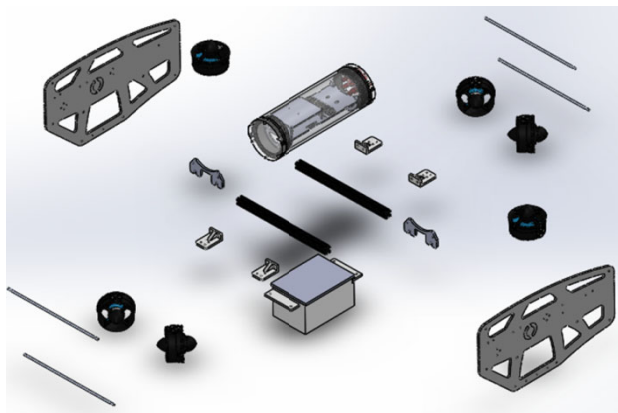
For the 3-blade propeller, thruster will undergo flow simulation. The rotating region of the flow simulation will be the 3-blade propeller which is inserted by selecting a newly created cylindrical part which covered the propeller. For the boundary region will be the real wall and stator of the rotor. The analysis will carry out at 4200 RPM which is the maximum angular speed given to the thruster resulting in a goal of force respect to the y-axis. The resultant velocity and force are plotted in the graph. Equation (2) shows that the acceleration of thruster can be calculated by force divided by the mass of the AUV.
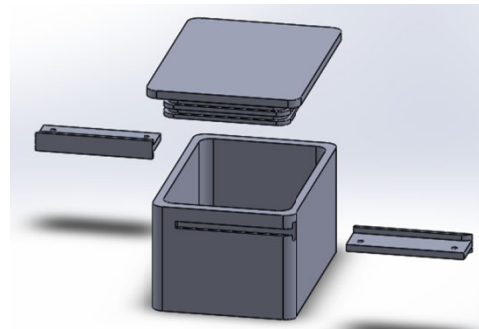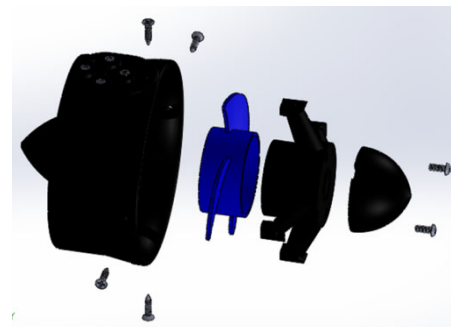

Fig. 6 — Explode view of the enclosure box

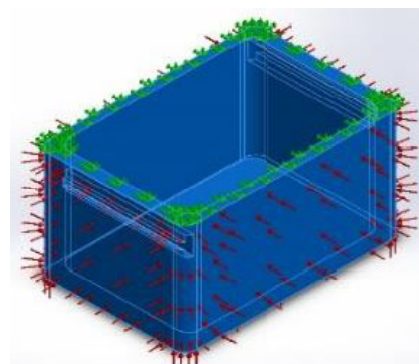Fig. 7 — Explode view of the thruster

Fig. 5 — Explode view of AUV

Fig. 8 — Pressure definition on enclosure box

$F = Ma$ ... (2)

where

F = Force (N)

M = Mass (kg)

a = Acceleration (m/s^2)

Modelling of AUV

Modelling of AUV dynamics can be derived from the dynamics equation of motion of UUV. The nonlinear dynamics equation of a 6-DOF AUV can be expressed as[11]:

$$m\dot{v} + C(v)v + D(v)v + g(\eta) = B(v)u$$ ... (3)

where,

m = Inertia matrix, including added mass

$C(v)$ = Matrix of Coriolis and centripetal frce's

$D(v)$ = Hydrodynamic damping matrix

$g(\eta)$ = Vector of gravitational forces and moments

$B(v)$ = Control input matrix

The velocity of the AUV is small because it is an open frame design where its speed is fixed based on dc motor performances. Therefore, some coupling terms can be neglected in the hydrodynamic mathematical model for the six equations of motions of the AUV. The equivalent 6 DOF can be expressed according to SNAME notation[12].

Since the ROV is assumed to be fairly symmetrical, it travels at a low speed and the decoupling for the vehicle degrees of freedom is valid. The decoupling means that the Coriolis and centripetal term's matrices become negligible and can be eliminated from the dynamic model. Then, the abridged nonlinear dynamic motion model for the AUV becomes

$$m\dot{v} + D(v)v + g(\eta) = B(v)u$$ ... (4)

The general expression of the inertial matrix M can be considerably simplified by exploiting different body symmetries. With the AUV frame positioned at the centre of gravity and since the vehicle is assumed fairly symmetrical at all axes, then the M_{RB} can be simplified to a good approximation to Equation (5)[13].

$$M_{RB} = \begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & I_X & 0 & 0 \\ 0 & 0 & 0 & 0 & I_Y & 0 \\ 0 & 0 & 0 & 0 & 0 & I_Z \end{bmatrix}$$ ... (5)

It can be seen from Equation (5) that the only parameter that needs identification for this matrix is the inertial moment about the z-axis corresponding to yaw. Analogous to the simplification of M_{RB}, the added mass matrix, M_A, becomes

$$M_A = \begin{bmatrix} X_{\dot{u}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_{\dot{w}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & N_{\dot{r}} \end{bmatrix}$$ ... (6)

The hydrodynamic damping matrix, $D(V)$, Equation (7)

$$D(v) = \begin{bmatrix} X_u + X_{u|u|}|u| & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_w + Z_{w|w|}|w| & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & N_r + N_{r|r|}|r| \end{bmatrix}$$ ... (7)

Given that the centres of gravity and buoyancy are aligned along the x- and y-axis, and hence the gravitational and buoyant forces should only affect the vertical movement.

$$G = \begin{bmatrix} 0 \\ 0 \\ -(B-W)\cos\phi\cos\theta \\ 0 \\ 0 \\ 0 \end{bmatrix}$$ ...(8)

Results and Discussion

The purpose of this analysis is to find out the center of gravity mass of the AUV. Center of gravity does not appear in SolidWorks by default, but it can be shown in drawing by following the procedures stated above. This application calculates properties including mass, density, volume constructed model geometry, and material things. Center of gravity is a geometric stuff for any item and typical position of the weight of an object. The location of the center of gravity is an essential parameter to determine the AUV characteristics of an object as shown in Figure 9.

Based on the mass properties Table 1 clearly shows that the center of gravity for AUV is placed at 42.28 cm X-axis, 55.48 cm Y-axis, and 42.56 cm

Z-axis. The COM also simulate for AUV mechanical parts including frame, hull, enclosure box, and thruster. Figure 10 shows the mass properties of AUV design. Then all parameters from Solidworks can be used to model the AUV as shown in Figure 11 by using MATLAB.

Figures 12, 13 and 14 show the AUV equipped with power supply circuit including Arduino UNO, depth sensor MPX5700AP, 10 DOF IMU sensor, AfroESC 30A, 9V Energizer battery and 12V lead-acid battery. The power supply provides 12V direct from the battery to ESC for thrusters while 9V battery supplies power to Arduino to function. ESC is electronic speed controller for motor propeller thruster. Pressure sensor MPX 5700AP is used to measure pressure and AUV travel distance in the Z-axis can be called as a depth sensor. Figure 15 shows the AUV tested on swimming pool for desired depth and rotation.

The analysis of the enclosure box is first determined by applying 3 m underwater pressure to the box as shown in Tables 2 to 4. The different pressures exerted to the box will be simulated by using 1 m depth until 10 m depth and the result is tabulated in Table 5.

From the result in Table 2, the maximum stress 2.457 MN/m^2 is in the enclosure box since only 29.43 kN/m^2 is applied. By referring to the safety factor the material is fully safe (in blue color). PLA has 59.984 MN/m^2 yield strength. The relation between the depth and maximum stress on the box is taken by simulating from 1 m depth until 10 m depth is ploted in the graph as shown in Figure 16. The yield strength of the material used can withstand up to 59.984 MN/m^2
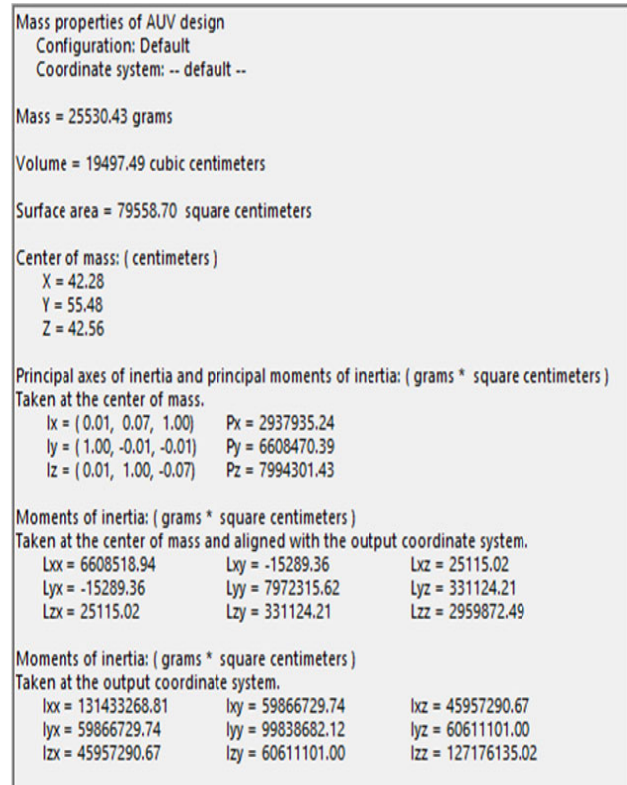

Figure 10 — Result of mass properties form SolidWorks

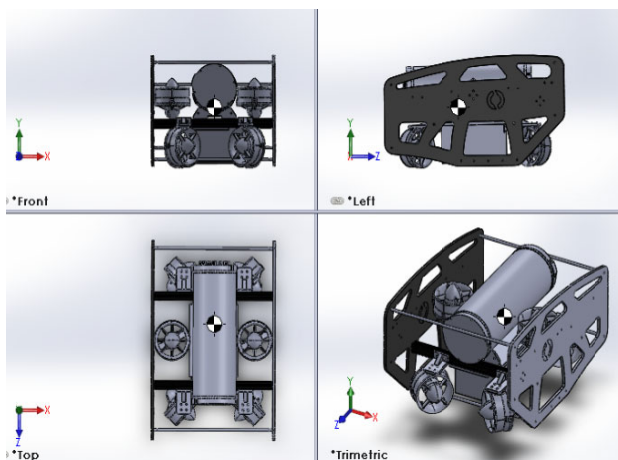Fig. 9 — Design AUV using Solidworks

Table 1 — Center of mass in SolidWorks Mass Properties

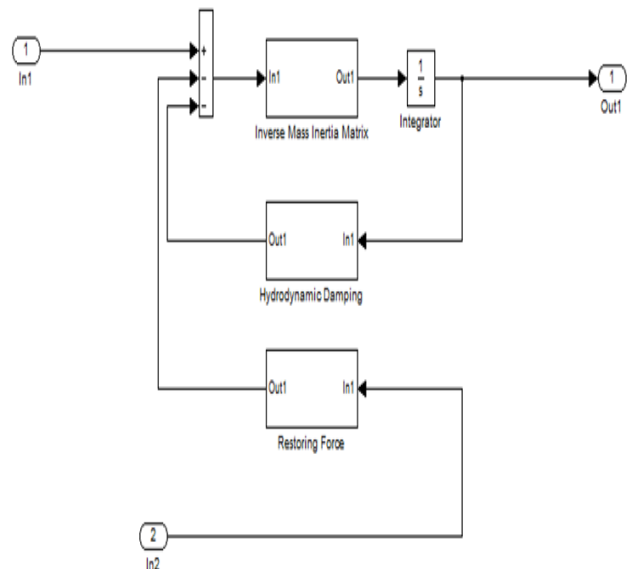| Axis	Center of mass (cm)
X	42.28
Y	55.48
Z	42.56

Fig. 11 — Modelling of AUV using MATLAB

Let M is the gradient of the graph

$$M = \frac{7372k - 5733k}{9 - 7} = 819500$$

$$\frac{59974k - 7372k}{h - 9} = = 819500$$

h = 73.2 m

The maximum depth of the enclosure box can go under water is about 73.2 m to ensure the box is without permanent deformation. The permanent deformation will start after the box goes beyond this maximum depth. Table 5 shows the result of the SolidWorks simulation.

The result for the flow simulation is determined by setting the maximum value of 4200 RPM of T100 thruster and the maximum velocity is obtained as
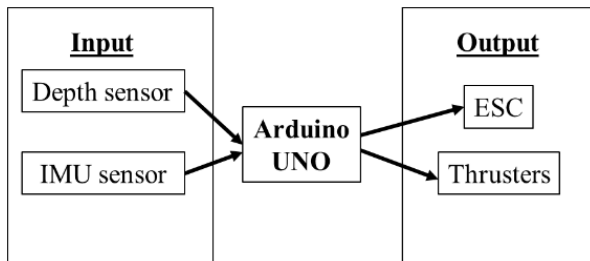
Fig. 12 — Block diagram of the embedded system design

(a)

(b)

Fig. 13 — BlueROV frame

shown in Figure 17. After running the rotational region, flow trajectory and cut plot can be a view to identifying the streamline of water flow as shown in Figure 18. The global goal (GG) of the maximum velocity of flow in the y-axis is about 4.939 m/s and
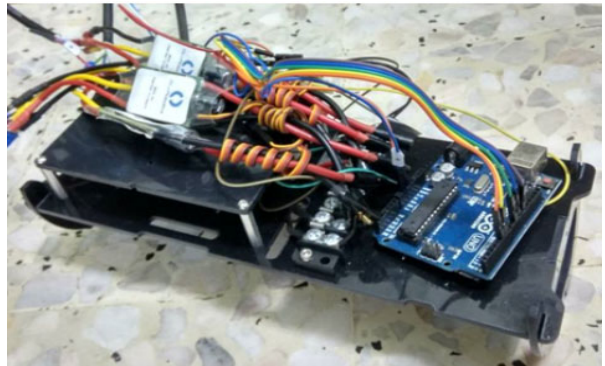
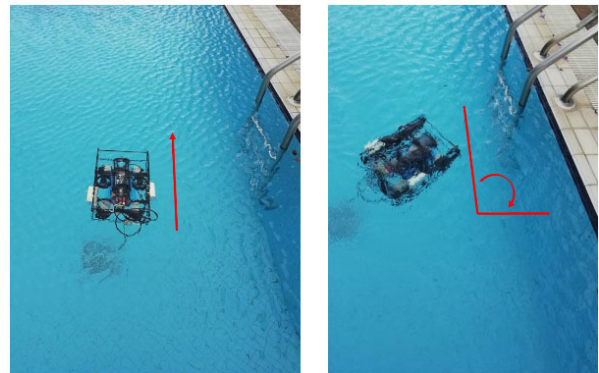Fig. 14 — Electrical component with electronics tray

Fig. 15 — AUV testing on swimming pool for desired depth

Table 2 — Study Results for Stress

Name	Type	Min	Max
Stress	Von Mises Stress	7.065e+003N/m^2 Node: 3394	2.457e+006N/m^2 Node: 7080

Enclosure Box-SimulationXpress Study-Stress-Stress

Table 3 — Study Results for Displacement

Name	Type	Min	Max
Displacement	Resultant Displacement	0.000e+000mm Node: 1	2.668e-001mm Node: 9059

Enclosure Box-SimulationXpress Study-Displacement-Displacement

Table 4 — Study Results for Factor of safety

Name	Type	Min	Max
Factor of Safety	Max von Mises Stress	2.441e+001 Node: 7080	8.491e+003 Node: 3394
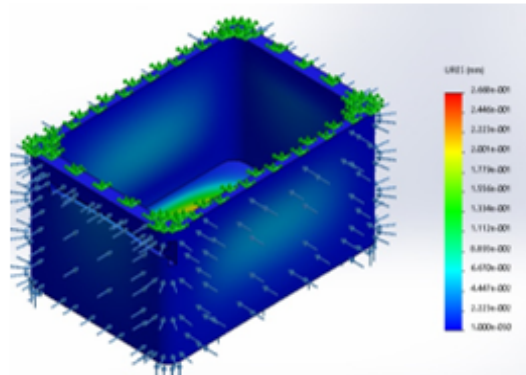
Enclosure Box-SimulationXpress Study-Factor of Safety-Factor of Safety

Table 5 — Relation between depths, water pressure, max stress

Depth (m)	Water pressure (kN/m2)	Max stress (kN/m2)
1	9.81	819.1
2	19.62	1638
3	29.43	2457
4	39.24	3276
5	49.05	4095
6	58.86	4914
7	68.67	5733
8	78.48	6553
9	88.29	7372
10	98.10	8191
73.2 (Permanent deformation start)	718.10	59960

the value of velocity comes to 4.7791 m/s. From the graph, at the first 10 iterations, it is shown that the velocity is overshooting very high at about 9.05 m/s and the graph drops to a more stable velocity when reaching 40th iteration.

The forces of thruster are analyzed by using surface goal (SG) on the y-axis. There are six faces of the propeller: the first three from the top of the rotor and the next three are from the bottom of the rotor. Figures 18 to 25 show the force of each SG force in the y-axis. For SG force (Y) 1, SG force (Y) 2 and SG force (Y) 3 are -5.004N, -8.3295N and -4.4709N, respectively. A negative value of the force representing the opposite direction of the force applies to the global y-axis. On the other side, SG force (Y) 4, SG force (Y) 5 and SG force (Y) 6 have the value of 2.8212N, 2.0433N and 1.6277N, respectively. A positive sign of force means the direction of the force is the same as the global y-axis.

Total thrust from the rotor is the summation of SG force 1 (y) until SG force 6 (y) which is about 11.31N opposite the Y-direction. As the design of the AUV is using four horizontal thrusters and the total AUV thrust becomes 45.24N. From Equation (2), acceleration of the AUV can be calculated, where the mass of the AUV is 8 kg from the measurement.

$a = F/m$

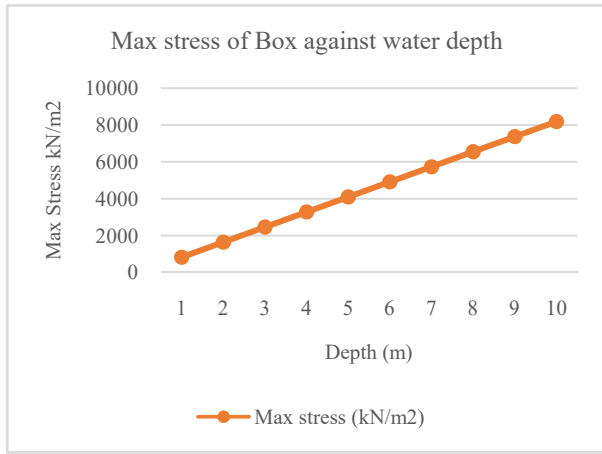$a = 45.24N/ 8kg$

$= 5.655 \text{ m/s}^2$

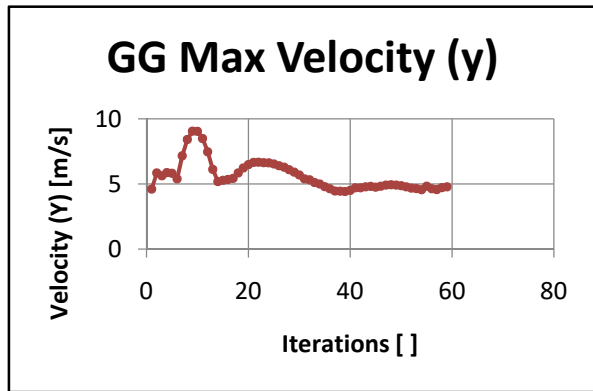Fig. 16 — Graph of Maximum stress versus water depth

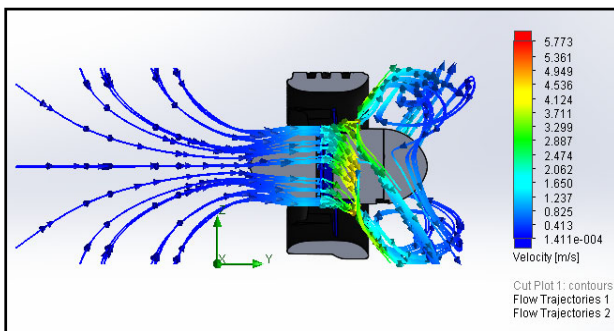Fig. 17 — Global goal of maximum velocity in y-axis
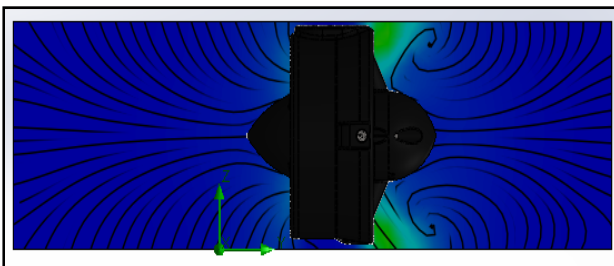

Fig. 18 — Section view of the flow trajectory

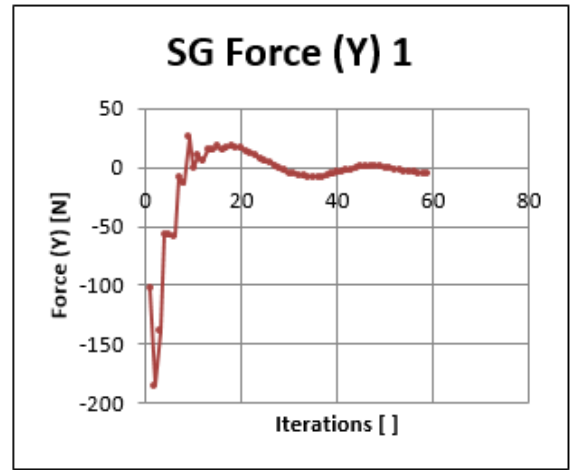Fig.19 — Cut plot of water streamline
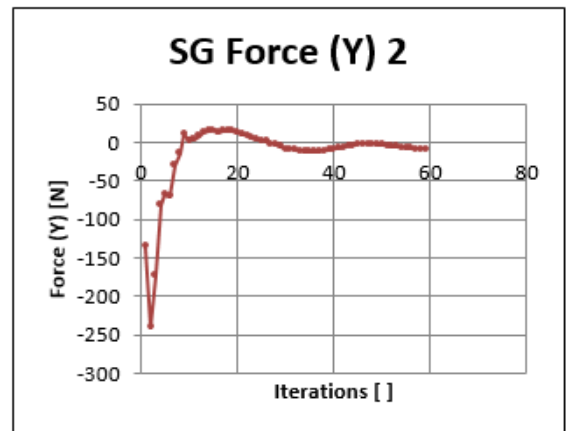

Fig. 20 — Surface goal of Force 1
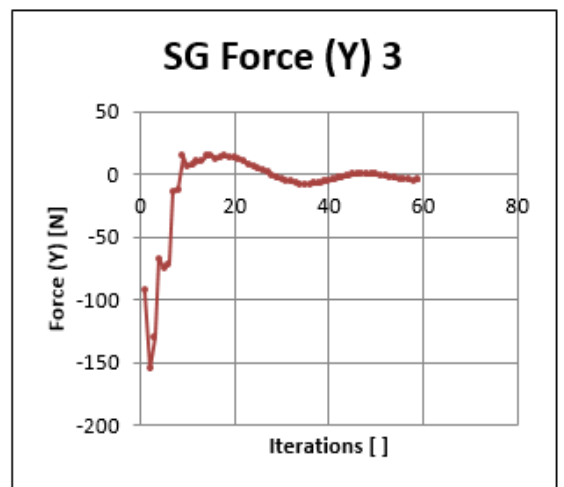

Fig. 21 — Surface goal of Force 2
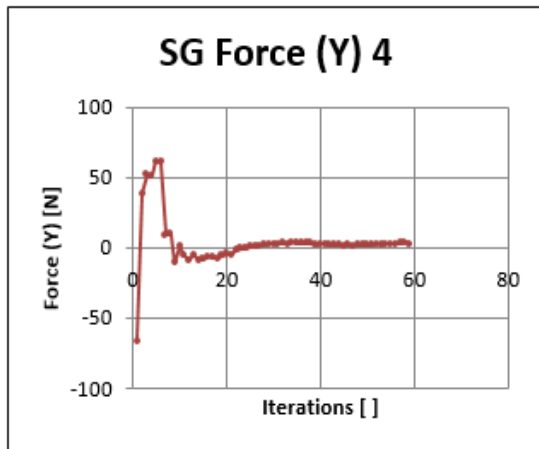

Fig. 22 — Surface goal of Force 3
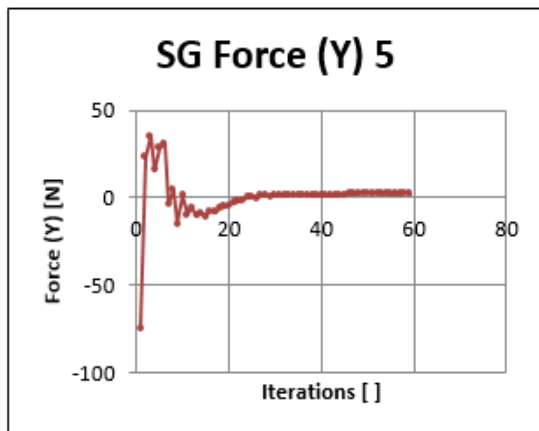
Fig. 23 — Surface goal of Force 4
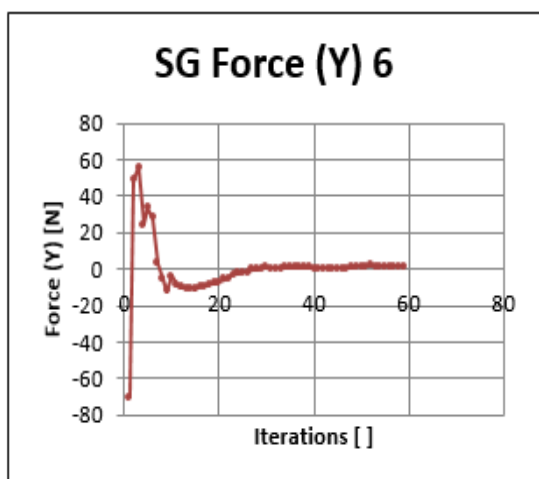

Fig. 24 — Surface goal of Force 5

Fig. 25 — Surface goal of Force 6

Conclusion

In this paper, the result obtained from the stress and strain simulation show the maximum depth that AUV can reach without the plastic deformation.

Besides, flow simulation provides tools for testing 3-blade propeller T100 thruster's maximum velocity with the high RPM of the thruster. Furthermore, goal plot in flow simulation also shows the thruster force acting on each side of the blade, and then the overall acceleration of AUV defined. In conclusion, SolidWorks is the useful software to present the design, modeling, assembly, and simulation of the AUV. The analysis done in SolidWorks is the easy and quick detection of an error in designing the parts.

Acknowledgment

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