Lap Time Predictions : Makara 'MAK-1'

Aim :

To compute added mass of MAK-1 and subsequently calculate the lap time of the AUV for Round 1 of the competition.

CAD Design:

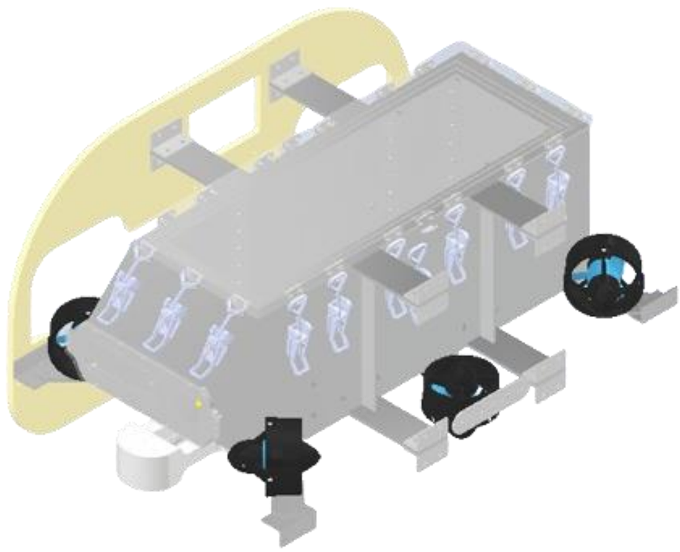

Figure 1 : Makara 'MAK-1'

Simplified CAD :

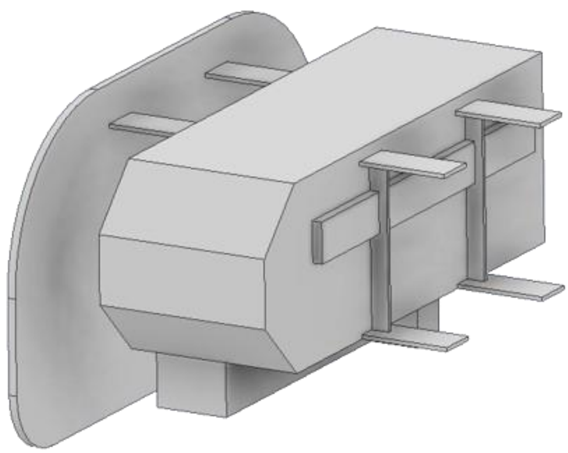

Figure 2 : MAK-1 simplified

The CAD was simplified to reduce computational complexity of the simulation.
Simple extrusions replace the robotic arm and latches.
The missing sideboard was removed for representational purposes only.

Theory :

For a body accelerating in a viscous fluid, the forces acting on it include – gravity, buoyancy, thrust force due to propulsion, viscous drag and added mass. Only the latter three being relevant when the direction of acceleration is perpendicular to that of gravity and buoyancy (our case.)
A body accelerating in the manner stated above, experiences 2 kinds of opposing forces – viscous drag proportional to the velocity of the body and added mass force proportional to the acceleration of the body.
The total opposing force can be computed using a CFD simulation for drag under transience.

Simulation Setup :

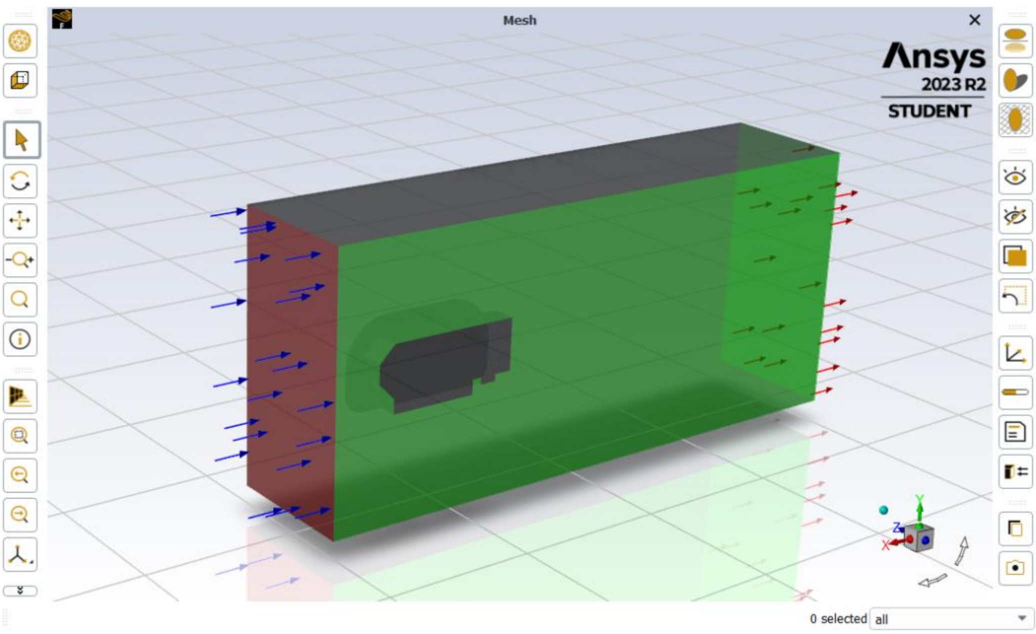

Figure 3 : Wind tunnel Scene

The wind tunnel was created in ANSYS Discovery and is large enough not to interfere with the wake of the body.
The body being mostly symmetric about the y-z plane, the simulation was performed for only **half of the volume** to reduce computational complexity. Results of the simulation should be **doubled** keeping in mind this fact.

Simulation Parameters :
Solver : Transient
Physics model – SSTKW
Method : PISO
Fluid – Water
Solid – Aluminum
Inlet Velocity – user defined velocity profile
Outlet pressure – 0 Pa

Simulation Results :

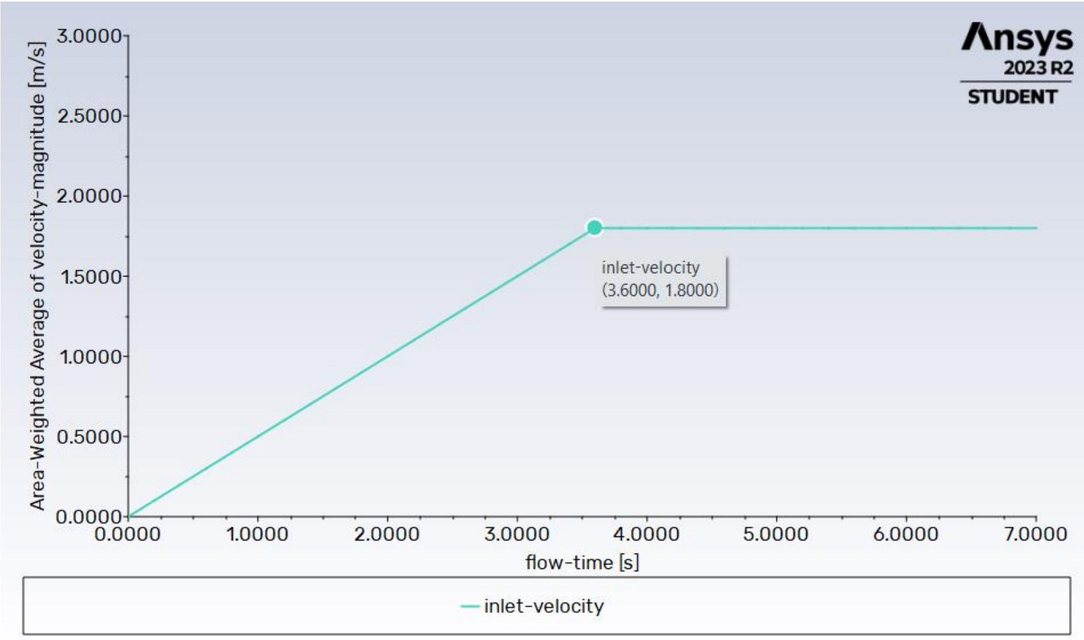

Figure 4 : inlet velocity

A user defined function was written for the velocity profile simulated at the inlet.
The velocity peaks at 1.8 ms^{-1} corresponding to the terminal velocity calculated earlier (Drag Report.pdf) and flat lines.
Acceleration of unsteady motion :

- ⇨ $a = (v - u)/t$
- ⇨ $a = (1.8 - 0)/ 3.6$
- ⇨ **$a = 0.5\ ms^{-2}$**

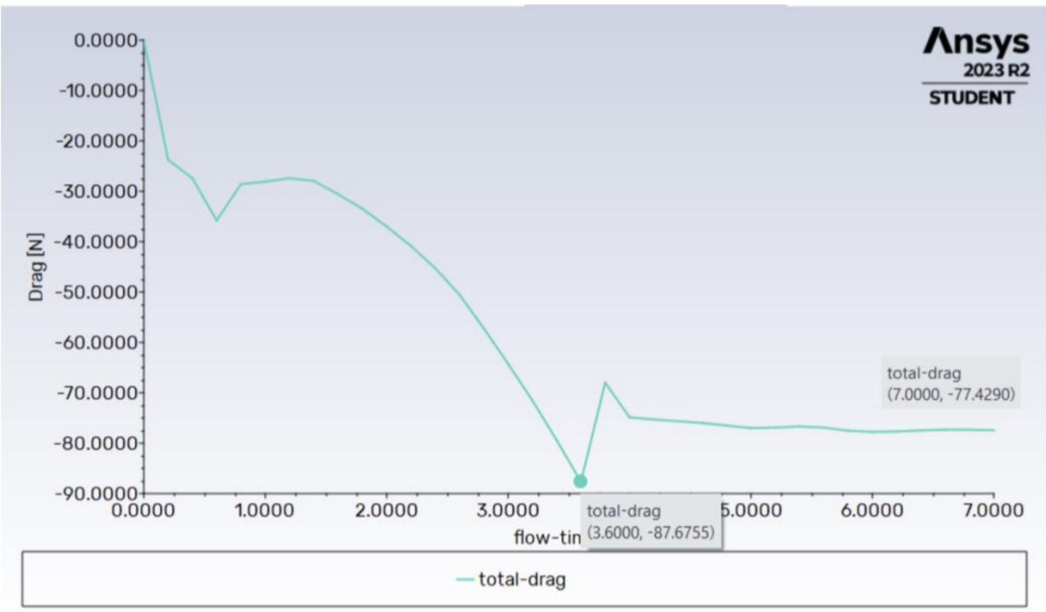

Figure 5 : Total Drag during transience

Added Mass Calculations :

During steady motion,

Simulation Drag (S) = Viscous Drag force (V)

V = 77.43 N

During unsteady motion,

Simulation Drag (S) = Viscous Drag (V) + Added Mass Force (A)

$A = S_{1.8} – V_{1.8}$
A = 87.68 – 77.43
A = 10.25 N

Added Mass force (A) = Added Mass (m_A) x Acceleration (a)

$m_A = A/a$
$m_A = 10.25/0.5$
m_A = 20.5 Kg

To remove any doubts regarding the method used to compute the added mass of the AUV we should repeat the simulation for different flow conditions.
Let us assume body accelerates at 1 ms^{-2} instead of 0.5 ms^{-2} until a terminal velocity of 1.8 ms^{-1}.
Apart from making the comparison less tedious, the choice of acceleration is arbitrary.

Let's make a prediction :

Added Mass force (A) = Added Mass (m_A) x Acceleration (a)

A = 20.5 x 1
A = 20.5 N

Simulation Drag (S) = Viscous Drag (V) + Added Mass Force (A)

S = 77.43 + 20.5
S = 97.93 N

at a higher acceleration of 1 ms^{-1}, we should expect a maximum unsteady simulation drag of 97.93 N.

Simulation Results :

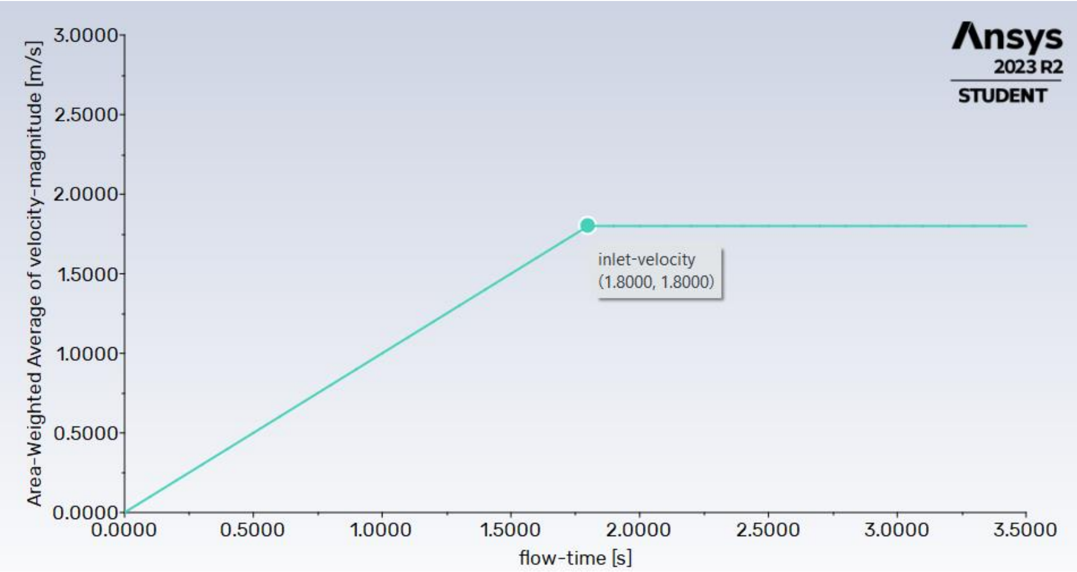

Figure 6 : inlet velocity

Another user defined function was written for the velocity profile simulated at the inlet. The velocity increases 1.8 ms^{-1} with an acceleration = 1 ms^{-2} and flat lines after 1.8 s.

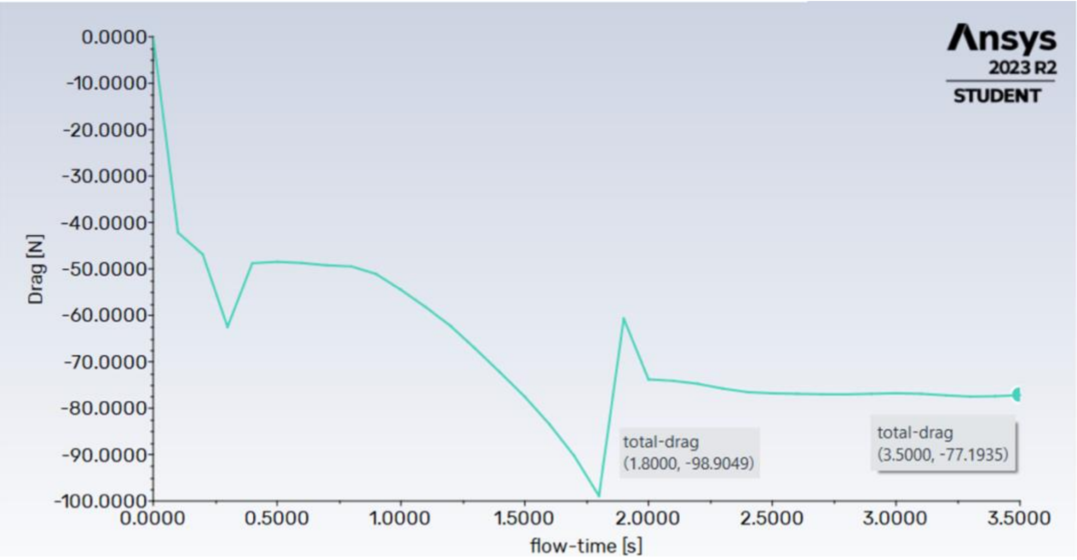

Figure 7 : Total drag during transience

The simulation drag is computed to be **98.9 N**, acceptably close to the predicted value. Therefore, added mass of the body is verified and remains constant for different flow conditions. This fact is important as the actual velocity profile of the AUV is exponential and features varying acceleration.

Note : The added mass computed here is only half the true value as the simulation is performed for only half the AUV. Hence, $\mathbf{m_A}$ **= 41 Kg**

Lap Time Calculations :

The mathematical model governing accelerated motion of the AUV in a viscous fluid due to self-propulsion is as follows :

$$F_T - kv^2 = (m + m_A)\frac{dv}{dt} \qquad Eq. 1$$

$$initial\ conditions: \ t = 0, v = 0, x = 0$$

Solving the differential equation with given initial conditions yields the following velocity – time relation for the AUV :

$$v = v_T \tanh\left(\frac{k.v_T}{m + m_A} t\right) \qquad Eq. 2$$

$$v_T = \sqrt{\frac{F_T}{k}} \qquad Eq. 3$$

Further integration yields the distance – time relationship :

$$x = \frac{m + m_A}{k} \ln\left(\cosh\left(\frac{k.v_T}{m + m_A} t\right)\right) \qquad Eq. 4$$

Here,

F_T : $Thrust\ force\ due\ to\ propulsion$
k : $Modified\ coefficient\ of\ drag$
v : $Velocity\ of\ AUV\ at\ time\ t$
m : $Mass\ of\ the\ AUV\ in\ air$
m_A : $Added\ Mass\ of\ the\ AUV$
v_T : $Terminal\ velocity\ of\ the\ AUV$

For 3 surge thrusters,

V_T = 1.8, F_T = 155 N, k = 47.84, m_A = 41 Kg. Assuming mass of AUV m = 25 Kg.
Substituting in Eq. 4 yields :

$$x = 1.37 \ln(\cosh(1.3\ t))$$

Similarly, for 2 surge thrusters, F_T = 103 N, V_T = 1.47 ms^{-1} :

$$x = 1.37 \ln(\cosh(1.07\ t))$$

And for 4 surge thrusters, F_T = 206 N, V_T = 2.07 ms^{-1} :

$$x = 1.37 \ln(\cosh(1.5\ t))$$

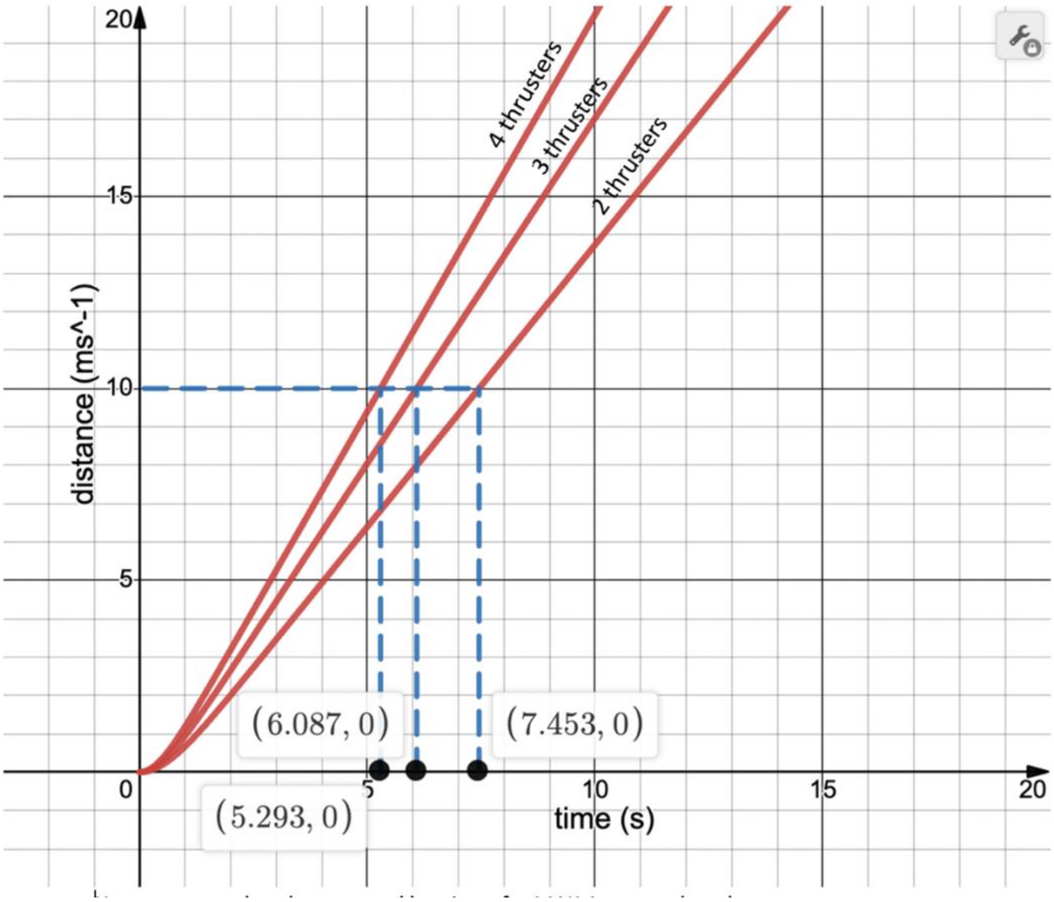

Figure 8 : Distance - Time Plots

Hence, we see that the expected lap times for MAK-1 at max throttle are :

2 surge thrusters – 7.453 s
3 surge thrusters – 6.087 s
4 surge thrusters – 5.293 s

It is worth investigating how the mass of the AUV affects its lap time,
Substituting x = 10 m in Eq. 4 :

$$t = \frac{m + m_A}{k.v_T} cosh^{-1}\left(\exp\left(\frac{10k}{m + m_A}\right)\right) \qquad Eq.5$$

Substituting the corresponding values for 2, 3 and 4 surge thrusters we get the following equations in order :

$$t = \ 0.94 \, cosh^{-1}(e^{7.25})$$

$$t = \ 0.77 \, cosh^{-1}(e^{7.25})$$

$$t = \ 0.67 \, cosh^{-1}(e^{7.25})$$

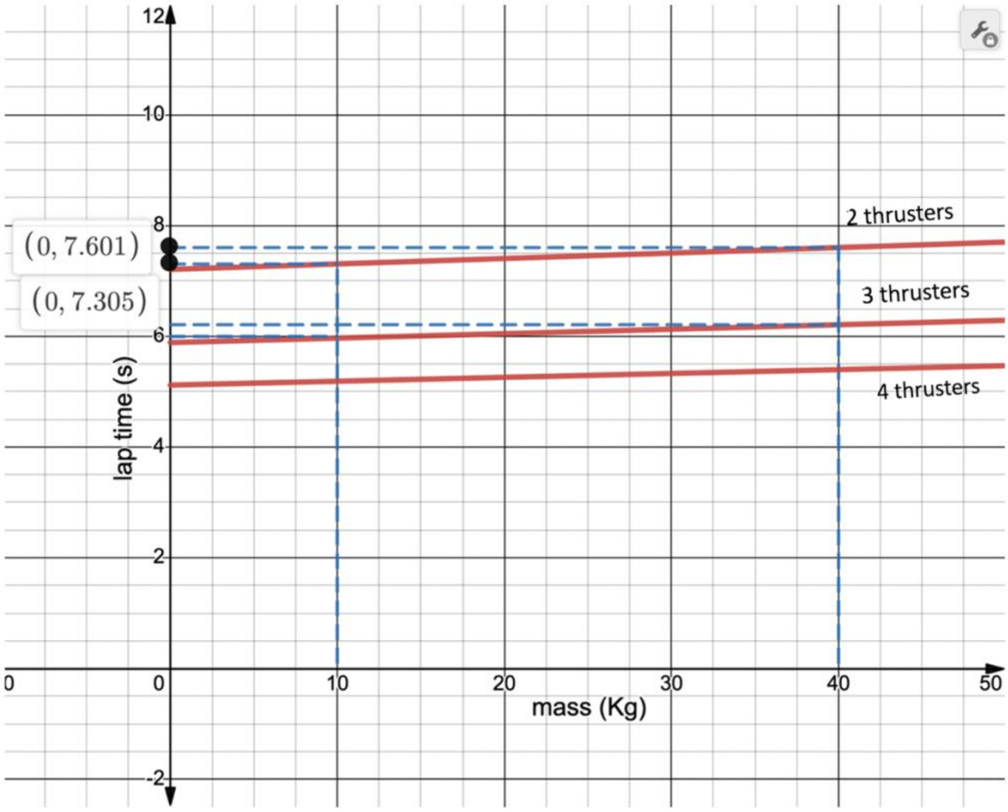

Figure 9 : Time - Mass Dependence

The plot above tells us that with current configuration, shaving up to 30 kgs will only earn us **0.3 s** during the race. And this time only decreases with increase in speed.

It can be seen that weight of the AUV has a **negligible** effect in the AUV's performance in Round 1 of the competition.

Since we can rule out mass of the AUV, the reason for MAK-1's sluggish motion compared to Black Pearl must be investigated further.

Notes :

At this point the weight of the AUV only affects its ease of transportation. The AUV need only be as heavy as one is willing to carry.
The weight of the AUV will not affect its performance in Round 1 or any other Round of the competition.

Regarding the sluggish motion of MAK-1, one important factor that was overlooked was that the 2 vehicles had different thrust angles. To accommodate the thrusters in MAK-1 the thrusters were oriented at 45° instead of 60° as was the case for Black Pearl.
This means that MAK-1 was only receiving 81 % of the thrust force propelling Black pearl. Another fact that should be considered is that MAK-1 was surging incorrectly and was simply rotating out of control. Consequently, never achieving terminal velocity. Therefore, we were misled into believing that MAK-1 was 'too slow.'

The reason for the unwanted rotation is yet to be conclusively identified. Possible reasons include inactive thruster(s), incorrect positioning of thruster(s) and bug in the program.

Another observation that was made during the shoot is that upon pulling the kill switch, MAK-1 was too slow to surface. This observation can be attributed entirely to the heavy weight of the vehicle. MAK-1 was very close to neutral buoyancy causing lesser net force, lesser acceleration, and lesser speed.

According to this report, we shall be outperforming the competition by a large margin. i.e. if the information about the lap times of the competing vehicles is in fact true.

The results also support the fact that 2 surge thrusters oriented in the forward direction are sufficient to achieve a lap time under 10 s.

The results of this report should be ratified by performing physical tests.

The terminal velocities for 2 and 4 surge thrusters are extrapolated and will be verified through simulations.

Since the weight of the AUV does not affect lap time, the weight can be increased until only 2 heave thrusters are sufficient to counteract buoyancy and the remaining 4 can be used as surge thrusters as in our previous design. But this arrangement has a persisting flaw, namely **no pitch control**. Hence the current arrangement is unacceptable and has to be revised.

It can be pointed out that distributing the 6 thrusters – 4 for heave and 2 for surge is quite an inefficient utilization of resources given that our primary task is passing through a gate in the least time possible.

Since the mass of an AUV is not a concern, it can be concluded that dynamically, the most efficient utilization of 6 thrusters is – **3 heave and 3 surge** thrusters as implemented on 'Matsya – 6 IITB.'

In our case, the 3rd heave thrusters would have to be accommodated at the back of the AUV and doing so would require us to shorten the length of the hull lest we forfeit the bonus criterion for dimension constraints.
Shortening the hull would reduce the buoyant force experienced by the AUV thus facilitating effective heave without the need for a 4th heave thruster or adding dummy weights to the vehicle.

Of course, the decreased volume of the hull would accompany an increase in the complexity of electronics arrangement and mounting.
With further analysis and testing it should become apparent whether maximizing volume for ease of electronics access is worth sacrificing a surge thruster.

Conclusion :

It is imperative that we gather intelligence regarding the lap times sufficient for qualifying Round 1 of the competition.
Final Decision regarding the need for an extra surge thruster should be taken after the physical test runs.