Power Management of a 10-Thruster ROV Using an Auto-Configurable Algorithm

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***Abstract*—This paper discusses a novel approach to utilizing extra thrusters for additional vertical lift for an ROV. The approach uses an auto-configurable algorithm which enables the operator to switch between the standard configuration and the enhanced-lift configuration, without changing the power supply for the vehicle. The results of a modified bollard pull test and a weight lift experiment illustrating the performance of the new configuration are also presented. Figure 1 shows the ROV with the added thrusters.**

I. Background

Originally the observation class ROV would only carry cameras to provide a flying eye underwater. Over the years they have shrunk in size and grown in capabilities, where they can now do light work and carry larger pay loads. A typical mini ROV will only have vertical thrusters to dive and lift the vehicle and are not purposed to perform lifting tasks. There are several underwater industries that require greater lifting capabilities for example: the nuclear industry [9], oceanography, wreckage recovery [1] and treasure hunting. These industries desire a vehicle that has those capabilities and is still man-portable, which has prompted the research into more advanced yet light weight systems to solve this problem.

Fig. 1. SeaLift ROV

The vertical thrust for a Teledyne SeaBotix standard mini *vLBV-300* ROV is provided by 2 vertical thrusters. These thrusters provide 88N of vertical thrust, resulting in the ability to lift 9kg underwater. The problem with using a regular vehicle other than the limit of 9kg is that the power is distributed evenly amongst all the thrusters, so the maximum amount of weight that a vehicle can lift is affected by the horizontal speed of the vehicle. In other words the vehicle can lift 9kg straight up, but not move forward at full speed with 9kg hanging from the lift point. The operator thus needs to be careful about how fast they can drive the vehicle in the horizontal direction so as to make sure that vertical lift is not impacted during the operation. This makes the challenge to lift more with the same portability even more challenging. Section II of this paper describes the methodology of deciding on the auto-configurable algorithm as the best solution to this problem. Section III details the mathematics and operation of the auto-configurable algorithm itself. The experimental validating results are presented in Section IV. The sections thereafter provide conclusions, follow on work and acknowledgements.

II. Methodology

There were various options that were looked at to obtain extra thrust in the vertical direction. Some of them are presented below.

A. Dropping weights and adding buoyancy

One method to increase the lift in water is to increase the buoyancy by increasing the volume of water displaced or by decreasing the density of the vehicle. An ROV could have extra weight added that it drops once it picks up the target. This provides positive buoyancy to the ROV and thus help offset the extra weight (target) being lifted. Some of the problems with this approach are that the user might not always know the payload weight beforehand and in case it turns out to be more than the weight being dropped, the lift would not be possible. The user also needs to make sure that the weights are dropped clear of the target and dont interfere with the intended lift. Another way is inflating lift bags from a compressed air tank and thereby achieving positive buoyancy by displacing water with air in the balloons. There are quite a few problems with this option as well. Firstly, it is cumbersome to carry a cylinder with a limited supply of air as it would need to be

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re-serviced frequently so as to be continuously in operation. Secondly, inflating the bags would also impact the stability of the vehicle and thus affect the flight performance.

B. Variable ballasting

Variable ballasting is another popular approach used to control the buoyancy of the vehicle. This has been accomplished in a couple of different ways like pumping water in and out of the ballast [2],or using an air compressor to control the amount of water in the tank. The compressor could either be on the vehicle [3] or on the surface [1] in which case the air is sent to the vehicle using the tether. All these methods need a sophisticated control mechanism for operating the ballast tanks and in case the compressed air is being sent from the surface, the tether also needs to be modified which means major hardware changes at both the top and bottom side to accommodate the new tether. The personnel involved also need to be trained on the correct operation of the ballast mechanism for a successful mission. While this could be a consideration for a completely different style ROV it is not feasible to add this mechanism onto the Teledyne SeaBotix ROV and still be man portable.

C. Larger thrusters with larger power supplies

Adding extra power with larger vertical thrusters to the system is another option that can help the vehicle lift more weight. A major problem with this option is the redesigning of the tether that would accompany this approach. The diameter of the tether must be kept to a minimum to enable ROVs to have long tethers. If the diameter of the tether increases; the drag as well as the vortex shedding that is known to occur with cylindrical objects in water will increase. [4] Since this diameter is dependent on the gauge of the conductors, adding more power to the system would invariably lead to its widening. Thus, adding more power to the system not only creates complexities with the power supply, but it decreases the performance of the vehicle with the additional drag force added to the tether. [5] One could of course add more power to compensate, but it will quickly lead to an ROV too big to be handled by a single person.

D. Additional Thrusters with an Auto-Configurable Algorithm

Knowing the pitfalls of other methods to increase lift, the method of adding additional thrusters to the standard ROV was decided upon. To allow this to work Teledyne SeaBotix came up with an auto-configurable algorithm. With this added capability the user can fly the ROV in its most basic configuration with only two vertical thrusters or add an extra four thrusters and use it as an enhanced lifting ROV. Another advancement that was developed to enhance lifting was the addition of a drop down armature and an additional camera. The ROV with this configuration is dubbed the SeaLift and is shown in Figure 2 with the armature in front and Figure 3 showing the armature deployed directly below the center of gravity and the center of buoyancy. This is to increase the stability while lifting. This approach had some obvious benefits over the other methods discussed in the paper. Firstly, it is very easy to configure. All the user needs to do is attach an extra four thrusters to the vehicle frame and power them through the already available connectors. Secondly, no re-designing of tether or an additional power supply is required, as there is no extra power that is being delivered to the vehicle, it is the same amount of power that is re-distributed unevenly to benefit the vertical thrusters more than the horizontal ones. Thirdly, since there is no one-shot equipment being used, there is no problem if the lift doesn't go right on the very first go. Also, since no extra complicated hardware is being added to the system the complexity of training the personnel is reduced by a huge margin. Once the methodology has been chosen the greatest challenges are calculating how many thrusters need to be added, how much power should be diverted to them and

Fig. 2. SeaLift with armature in front

Fig. 3. SeaLift with armature deployed

how well the ROV would fly forward while lifting heavier loads.

III. Algorithm Analysis

A. Calculation of Additional Thrust and Thrusters Needed

The Teledyne SeaBotix ROV has an electrical propulsion system. Based on the demand of the industry the goal of lifting 17kg while moving forward at 0.1m/s was set as the requirement. To calculate how much thrust is needed the drag on the vehicle is calculated so that the thrusters can be sized not only to lift the weight but also to overcome the drag in the vertical axis as well as the horizontal plane. [8] The drag equation is as follows:

$$F_d = \frac{1}{2}\rho u^2 C_d A$$

F_d Drag Force, Newtons
ρ Density of Fluid, kg/m^3
u Flow Velocity, m/s
C_d Coefficient of drag
A Reference Area, m^2

The drag force on the vehicle is a function of the square of the speed. Since we are more concerned with lifting than flying and the speeds will be low, the drag force will be insignificant to the lift force that is needed. This is convenient because it constrains the load to a near constant value. Once the load is defined the amount of power allocated to the thrusters and the resulting thrust must be calculated. The SeaLift has four horizontal thrusters that are angled in a manner that allows all of them to operate in any direction on the plane. This is called a vectored configuration. The vertical thrusters are only directed in the vertical axis.

To calculate the amount of thrust produced versus power available, the torque and rotations per minute (RPM) must be measured or known. The thrusters have internal RPM sensors as well as current meters so that the power draw can be measured. To calculate the thrust versus RPM the following equation can be examined from [7].

$$\Gamma = A_d \rho \eta^2 p^2 \Omega |\Omega|$$

Γ Thrust, Newtons
A_d Duct Reference Area, m^2
ρ Density of Fluid, kg/m^3
η Propeller Efficiency
p Blade Pitch, radians
Ω Propeller Angular Velocity, rad/s

Similar to drag on the vehicle, thrust is also produced as a function of the square of the propeller speed. The torque required to spin the thruster is also subject to drag and the power draw becomes more complicated to predict especially if the efficiencies are unknown. To estimate some of these parameters a system of equations must be established to define the coefficients. According to the work done by Healy et al [6] you can estimate the thrust, torque and speed of advance through the simplified equations.

$$C_\Gamma = \frac{\Gamma}{\rho n^2 \Phi^4}, C_q = \frac{Q}{\rho n^2 \Phi^5}, J = \frac{U_a}{n\Phi}$$

C_Γ Coefficient of thrust
Γ Thrust, Newtons
n Propeller RPS, rotations per second
ρ Density of Fluid, kg/m^3
C_q Coefficient of torque
Φ Propeller Diameter, meters
Q Propeller Torque, Nm
U_a Section Average Flow Velocity, m/s
J Speed of Advance, per rotation

These families of equations still do not provide a prediction without some assumptions and experimental validation. Simulations can be run to find these coefficients through iterations, but the software can be costly as well as difficult to use by the casual fluid dynamics engineer. Teledyne SeaBotix has access to a dock in a bay and experiments similar to the ones described in [6] were performed to measure the RPM versus Power and thrust versus power. The results of this Bollard pull test are shown in Figure 4. From this information and adding a safety factor to account for vehicle drag we estimated that with 4 additional vertical thrusters we can allocate 400W to horizontal motion while providing 195N lift force. The SeaLift has what is called gain settings to vary the amount of power allocated to an axis. At full vertical gain the SeaLift will not be able to move forward. A linear mapping was made to allocate vertical thrust versus horizontal thrust for lifting ability.

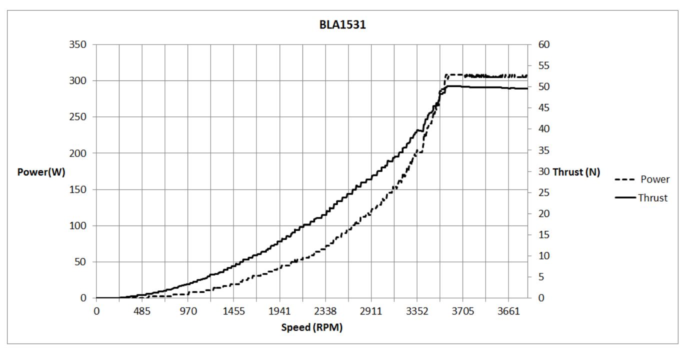

Fig. 4. Thrust Curve

B. Auto-Configuration

In a typical vLBV all of the thrusters have equal priority to the power and can be driven at the maximum speed allotted. To create the SeaLift we added 4 thrusters around the vehicle as described in previous sections. Gain settings are used to increase the amount of power available to the thrusters in horizontal or vertical axis. Low gains are used for fine movement while high gains are used for gross maneuvering at full power. With the addition of the extra vertical thrusters the amount of consumed power quickly reaches the maximum available on the ROV and the vertical thrusters thus need to be prioritized to lift various weights at various gain settings. With the auto-configurable algorithm, the vertical thrusters have a higher priority over the horizontal ones and as a result, are able to use more power at higher gains than their horizontal counterparts. This vertical lift is independent of the movement of the horizontal thrusters as the vehicle is no longer allocating power to all its thrusters in a proportionate manner. The user also does not need to send any special commands or use a specific configuration every time they want to switch to the Vertical Priority mode. The algorithm detects the extra thrusters and automatically switches to the SeaLift mode. If the user wishes to go back to the normal Equal Priority mode, they just need to disconnect and remove the extra thrusters and reset the vehicle power to allow the algorithm to detect the number of thrusters on the bus. Another benefit is that due to the preferential treatment to the vertical thrusters, a guaranteed thrust value is ensured at each vertical gain level. Also, as a result of this, an option of minimum amount of lift gives the maximum horizontal speed and an option of no horizontal movement leads to the maximum lift for the vehicle. The user can thus choose a vertical gain level that best fits their application. The calculation flowchart of the algorithm is shown in figure 5.

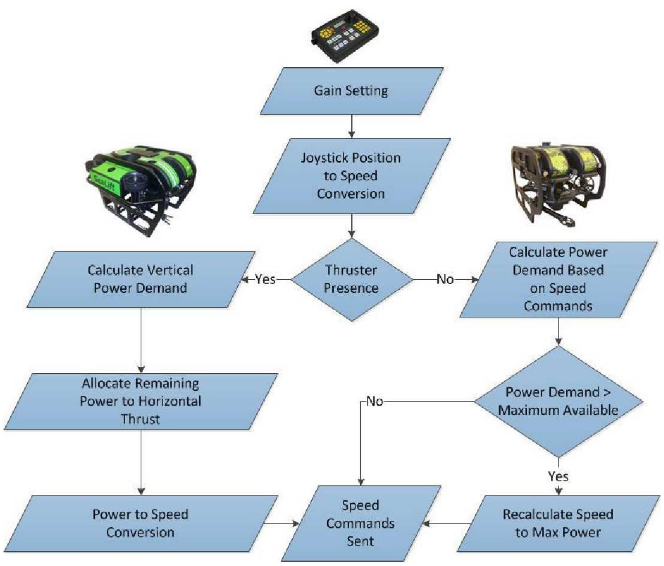

Fig. 5. Algorithm flowchart and ROV configurations, SeaLift (left) and standard (right)

IV. Experimental Validation

A. Modified bollard pull test

After the vehicle was fitted with the extra four thrusters and the auto-configurable algorithm loaded onto the main processor, a bollard pull test experiment was conducted to predict the amount of weight that the vehicle can lift at a particular gain setting. This experiment takes the basic principles of the static bollard test performed on a single thruster and applies it to the vehicle itself. The experiment setting consisted of a strain gauge and rigging set off the dock of the Teledyne SeaBotix facility with an entire vehicle. The experiment helped with both setting a baseline for the dynamic lift and speed test as well as a validation of the algorithm.The experiment setup is described in figure 6 and the results are presented in table I.

Gain	Avg. Force (weight) N (kg)	Variance
1	44.2 (4.5)	3.9 (0.4)
2	84.3 (8.6)	3.9 (0.4)
3	112.8 (11.5)	7.8 (0.8)
4	130.4 (13.3)	2.0 (0.2)
5	152.0 (15.5)	9.8 (1.0)
6	173.6 (17.1)	3.9 (0.4)
7	184.4 (18.8)	2.0 (0.2)
8	201.0 (20.5)	7.8 (0.8)
9	207.4 (21.15)	1.6 (0.16)
10	227.0 (23.15)	1.0 (0.10)

TABLE I
Bollard test data

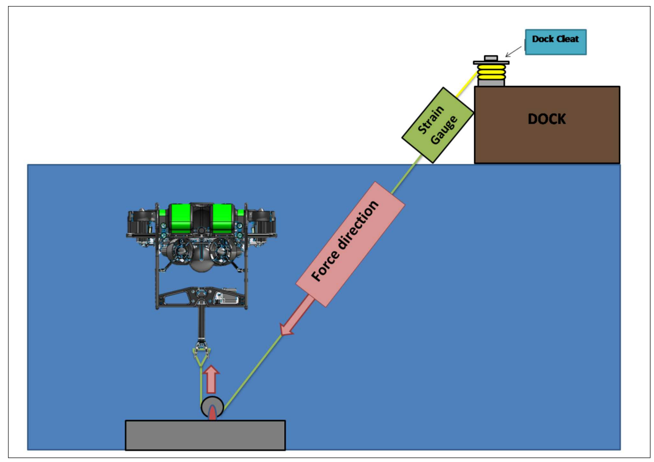

Fig. 6. Modified bollard test setup

B. Loaded Dynamic Speed Test

To measure the true performance of the power management algorithm an experiment was performed at a diver training tank at National University in San Diego. The test setup was to use known weights and adjust the gain for maximum forward motion. The vehicle was then timed between two reference points to measure its speed. This task was rather challenging since the speed in one dimension is sought yet the vehicle is flying in three dimensions. The tank itself will also be subject to turbulence if the vehicle is on for too long. While the experiment can be improved for more accurate readings this experiment is a good reference and an indication of minimum performance. The unit under test is shown in Figure 7 and the results are shown in Table II. The results of the experiment show that using the algorithm and four more standard Teledyne SeaBotix thrusters the ROV was able to lift well over double the amount of weight as a standard vehicle without having to increase the power available. It was also proven that the vehicle can move forward while lifting this weight.

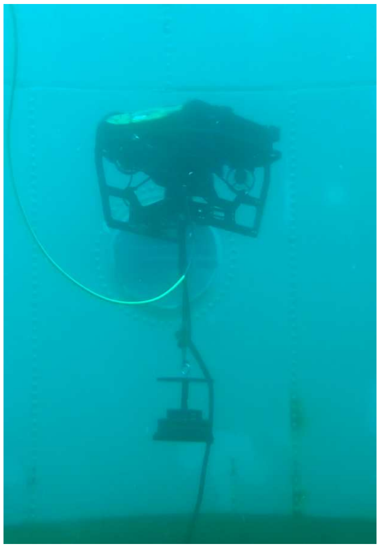

Fig. 7. Lifting weights with SeaLift

Distance (m)	Weight (kg)	Gain	Speed (m/s)
3	12.64	3	0.5
3	19.64	7	0.15
3	21.9	8	N/A

TABLE II
LOADED SPEED TEST RESULTS

V. CONCLUSION

Through the use of advanced algorithms, ROVs that are typically used for simple observation tasks can perform tasks that they were initially thought incapable of. This paper presented an auto-configurable algorithm that assigns more power to vertical thrusters than the horizontal ones when the vehicle is in the enhanced-lift configuration. The results show that SeaLift can carry more than twice the amount of weight as a standard configuration vehicle with the same amount of total available power and still be able to move in the horizontal plane. The future work involves enabling the ROV to sense the weight that it is picking up and reporting to the operator in relation to this algorithm. The use of auto-configurable algorithms will continue to grow as the demand for variations of mini ROVs continues. The addressing, communication, and configuration schemes will become more complicated but it will lead to a more versatile robotic workforce in the underwater industry, thereby adding more capabilities to the systems without putting divers in harms way.

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Fig. 8. National University testing facility

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