Deep Water MiniROVs and Delivery Systems

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***Abstract*—this paper presents the evolution of underwater Miniature Remote Operated Vehicles (MiniROVs) from shallow water to deep water applications. Shallow and deep are relative terms; in this paper we will consider shallow depth up to 500 m and deep water from 500 m up to 4000 m. Using the hydrodynamic aspects of water flow on long tethers due to ocean currents, this paper explores the justification for the different components of a modern deep water MiniROV system, including the Tether Management System (TMS) and Launch and Recovery System (LARS).**

Keywords—Underwater, Remote Operated Vehicle, ROV, Observation Class, vLBV300, vLBV950, vLBV2000, vLBV4000, Fly-Out, MiniROV, Clump weight, SeaBotix, Deep water, Tether Management System, TMS, Launch and Recovery System, LARS, Active Heave Compensation.

I. Introduction

In the last decade, the miniaturization and increase in production of Observation Class ROVs has driven the cost of an overall system down to a point where it is affordable for more applications. As the number of MiniROVs increase for shallow water applications <500 m, more and more operators are coming to the realization that for observation and light duty work in deeper water, MiniROVs offer the same performance as much larger ROVs without the higher cost of the equipment and commissioning. It is important to note that a MiniROV can be deployed from the side of a ship with a manual reel for shallow water applications, however clump weight systems or Tether Management Systems (TMS) are necessary for deployment in deeper waters. Typically, deep water ROVs fly out of the deployed TMS, hence the label Fly-Out Systems.

II. MiniROV Limitations

A. *MiniROV Depth Rating Over the Years*

Historically MiniROVs started to be used in very shallow water applications anywhere from 50 m to 150 m. Slowly operators started to request deeper rated vehicles for covering a wider spectrum of applications. Today most MiniROVs are used within the first 300 m of water.

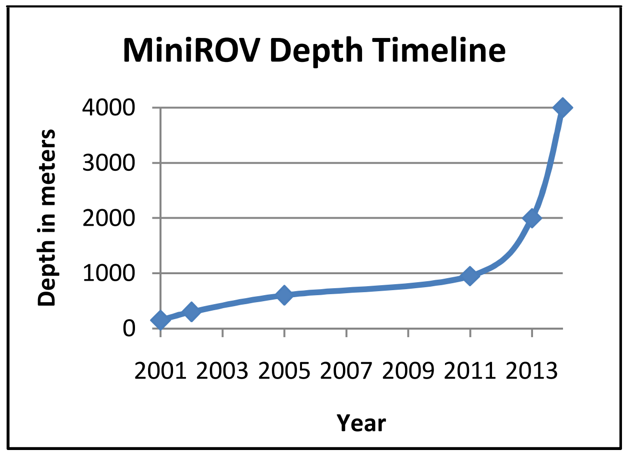

Fig. 1. MiniROV Depth Timeline [1]

There are some technical challenges in producing MiniROVs capable of operating in greater depths than 1000 m, including but not limited to:

1. Miniaturization of control electronics and design of light weight pressure housings.
2. Oil compensated pressure balanced housings for thrusters and actuators.
3. Power transmission over long cable lengths.
4. Data transmission over long cable lengths.
5. Increased floatation volume due to higher density foams.

The challenges listed above have been addressed by various technological advancements enabling vehicles to operate down to 4000 m depths. As history shows on Fig. 1, depth ratings of MiniROVs keep increasing, but in order to operate a MiniROV deeper than 1000 m, the maneuverability limitations of the ROV need to be considered rather than its resistance to high pressure.

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B. *MiniROV Free-Swimming Maneuverability*

We will define the maneuverability of an ROV as its ability to overcome external forces in its environment to produce motion. Vertical and horizontal motions are generated by the ROV thrusters and they must overcome the ROV weight or buoyancy, the drag generated by the water flow on the ROV and finally the drag generated by the tether. Peak ROV performance is achieved with short tethers. As the tether length increases, it becomes less maneuverable and less predictable, to the point where the drag of the tether becomes more than what the ROV can "pull" or handle. The drag on the tether is a function of:

1. Tether length
2. Water velocity
3. Tether cross section
4. Tether texture

The deeper the MiniROV needs to operate, the longer the tether length. Water velocity on the tether is a function of the ROV speed as well as the water current in the environment.

Tether cross section is a function of the technology that is used for transmitting power and data over long distances in a neutrally buoyant package that can withstand the depth rating. Tether texture has only a small effect on the drag. Typically tethers are smooth cylinders to reduce the drag coefficient. As illustrated on Fig. 2, water flow applied to a smooth cylinder creates drag. The tether drag can be calculated using the following equation:

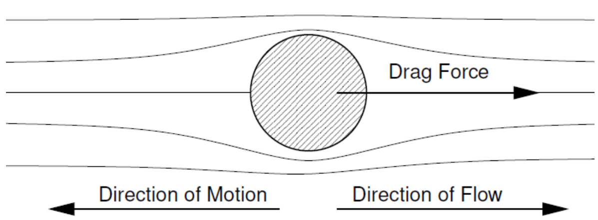

Fig. 2. Drag Froces on a Cylinder [2].

$$F_l = \frac{1}{2}.\rho.v^2.C_d.d.l \qquad (1)$$

Where F_l is the drag force for cylinder of length l

ρ is the density of water

v is the velocity of the water

C_d is the coefficient of drag

d is the diameter of the cylinder

l is the cylinder length

For calculations, a typical value for salt water density is 1030 kg/m^3. For water velocity of 0.5-3 knot (kt), the Reynolds numbers are 2.65×10^3 and 15.9×10^3 for a ~10 mm smooth cylinder, the coefficient of drag is relatively constant at 1.2 as shown on the graph Fig. 3.

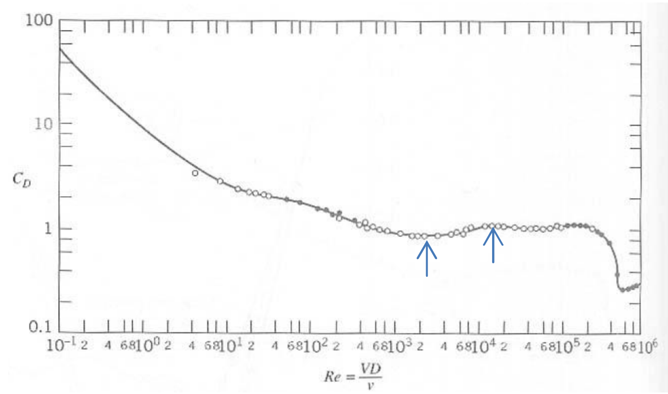

Fig. 3. Variation of Cylinder-drag Coefficient with Reynolds Number [3]

As shown on Fig. 4, in order to stay maneuverable, the ROV needs to generate more thrust than the sum of the drag generated by its profile in the water plus the drag generated by the tether.

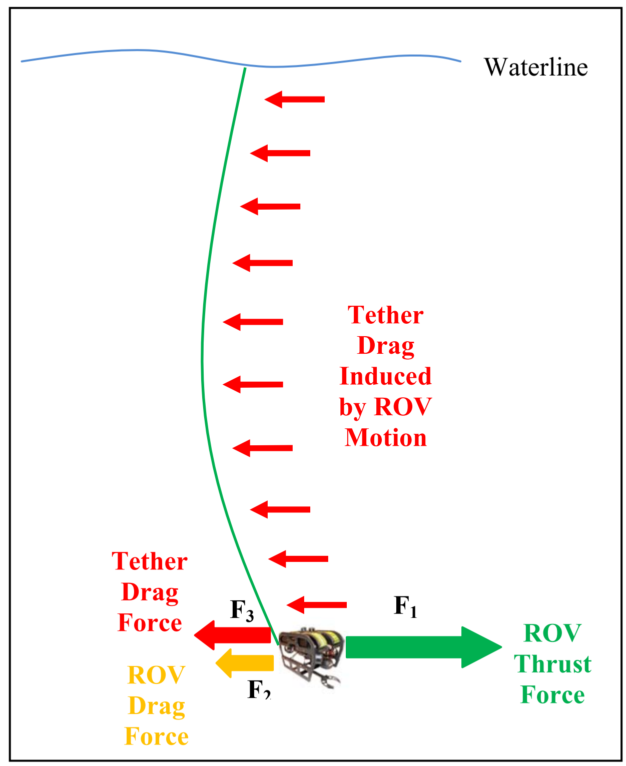

Fig. 4. Drag Induced by a Long Tether.

$$F_1 \geq F_2 + F_3 \qquad (2)$$

Where F_1 is the force generated by ROV thrusters

F_2 is drag force on the ROV

F_3 is tether drag force applied to the ROV

For a typical deployment from a small vessel where the ROV is located below the ship, the tether will make an arc in the water. In order to simplify calculations, we will consider the following assumptions:

1. Tether is in a straight line rather than an arc.
2. Tether is fixed on the surface vessel.
3. No current, the only drag on the tether is generated by the ROV's own speed.

With the tether attached to a fixed point at the surface and to the ROV on the other side, we can assume a rotating "pendulum" system in order to calculate the force the ROV has to overcome in order to drag the tether through the water. A simple moment calculation can be applied:

$$F_3 = \frac{M_{3ROV}}{L} \quad (2)$$

Where M_{3ROV} is the moment of tether drag forces applied to the ROV

F_3 is tether drag force applied to the ROV

L is the tether length (moment arm)

As illustrated on Fig. 5, with the assumption of the fixed point at the surface and a moving point at the bottom where the ROV is located, the force F_3 applied to the ROV as a result of the tether drag is the sum of the moments along the length taking into account the water velocity for each segment, divided by the overall tether length. The calculation for F_3 becomes:

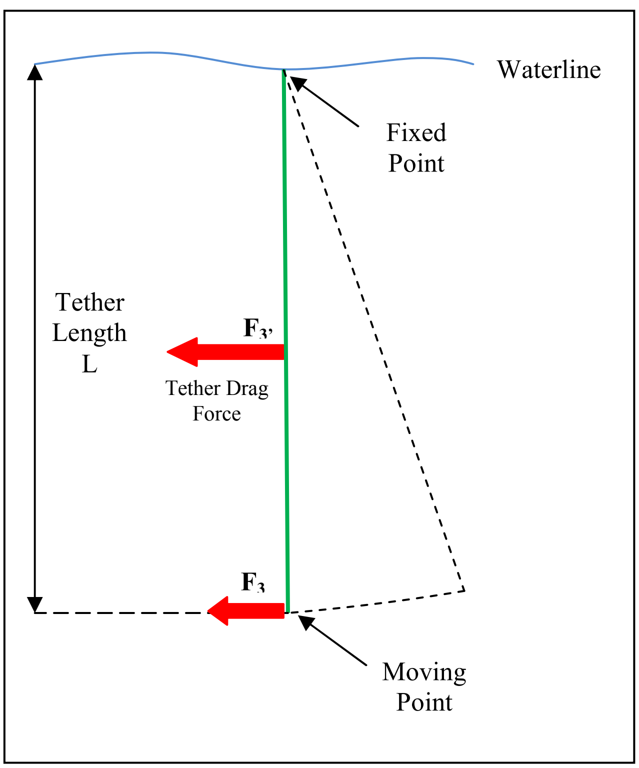

Fig. 5. Drag Induced by a Long Tether.

$$F_3 = \frac{\sum_{k=0}^{n} F_k \times L_k}{L} \quad (3)$$

Where F_3 is the tether drag force applied to the ROV

F_k is the tether drag force at segment k

L_k is the tether length at segment k

L is the full tether length

n is the number of segments

The ROV thrust force F_1 generated by a combination of thrusters is a function of the ROV drag due to its profile moving in the water and the mechanical thrust generated by the thrusters at different speeds. An ROV is dynamically characterized when the thrust versus speed curve has been generated. This curve is a function of the square of the velocity as illustrated on Fig. 6.

$$F_1 = K_t . v^2 \quad (4)$$

Where F_1 is ROV Thrust force

K_t is the thrust coefficient

v is the water velocity

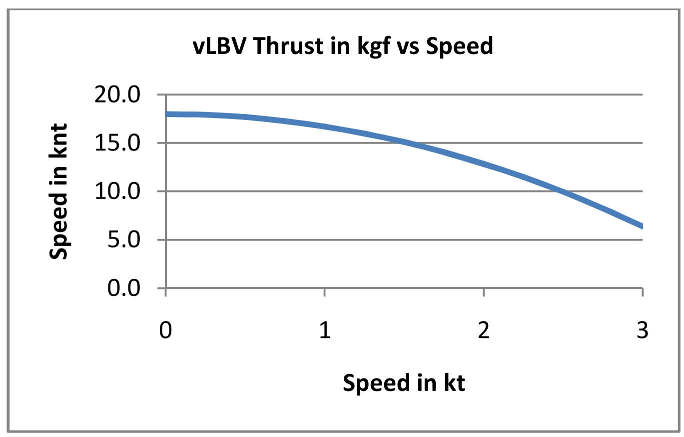

Fig. 6. SeaBotix vLBV950 Dynamic Model.

The assumptions above allow considerable calculation simplifications to quickly help evaluate the maximum tether length a particular ROV can handle and still remain maneuverable.

Using the SeaBotix vLBV950 dynamic model and the tether drag equations above, the calculation shows the ROV can be free swimming at a maximum depth of 950 m with no current. However, at this depth when the ROV makes way horizontally, it is dragging 950 m of umbilical through the entire water column. The drag received by the 9mm umbilical over 950 m length is enough to slow down the ROV normally capable of ~3 kt, down to 0.65 kt. With the ROV free swimming, if we add 1 kt of current for the first 200 m of water below the surface, the calculations clearly show the ROV will not be maneuverable anymore. This is where a clump weight is needed.

C. MiniROV Maneuverability with a Clump Weight

The clump weight is a method to remove the effect of the tether drag from the ROV as shown on Fig. 7. As analyzed in the previous section, the water flow along the tether generates drag that is eventually applied to the ROV. In order to isolate the ROV from most of the tether drag, a clump weight is utilized to stabilize the section of the tether that is subjected to the most drag, providing a short section for the ROV to free swim.

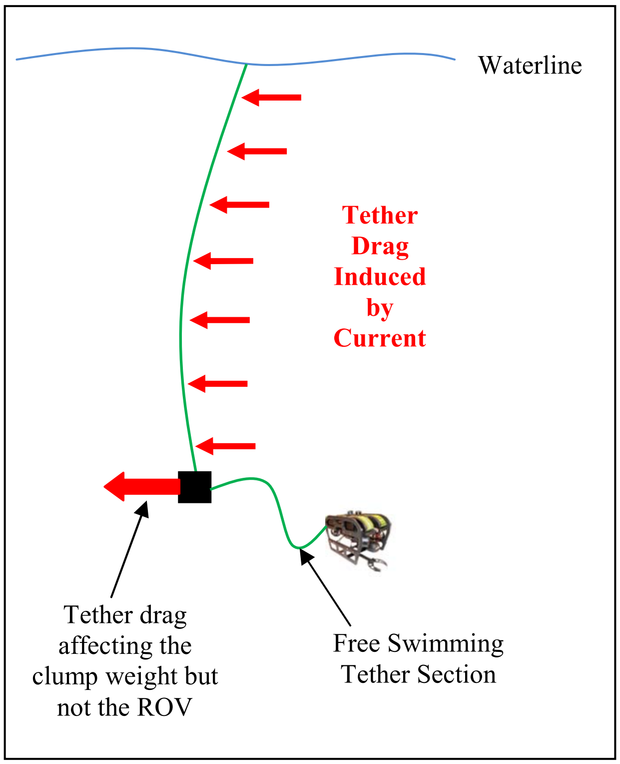

Fig. 7. Clump Weight Method.

There are however several issues when using a clump weight. The current takes the clump weight away from the intended target over the ground. The deployment and retrieval of an ROV and clump weight is challenging and requires skilled operators. Finally the free swimming section is typically short, which limits the excursion capability of the ROV.

1) Off-Target Offset when using a Clump Weight

The off-target offset distance is the horizontal distance the clump weight is being moved away from its vertical position due to current as depicted on Fig. 8. With little or no current, the Global Positioning System (GPS) position of

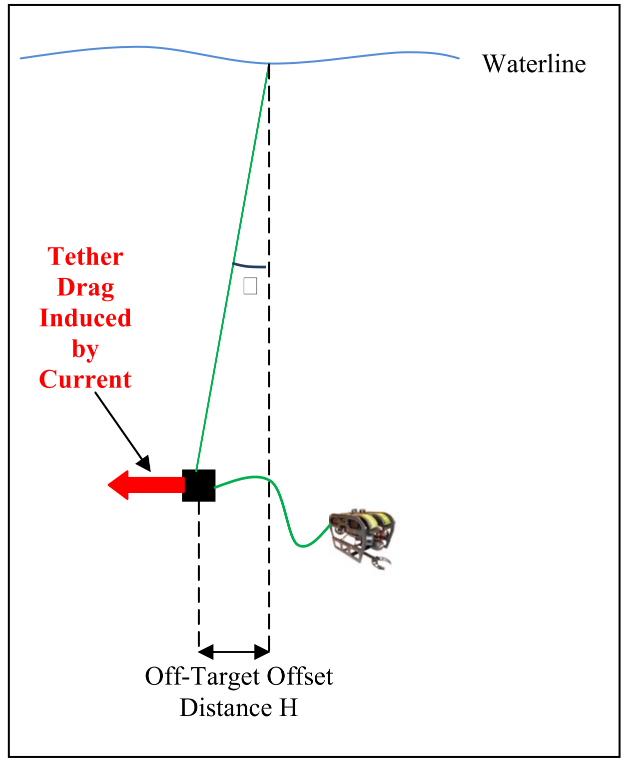

Fig. 8. Off-Target Distance with Clump Weight Method.

the ship is the same as the position of the clump weight. However when current is applied to the tether, the clump weight is offset from the wanted position. This offset is a function of clump weight and drag forces applied to the tether length. F_3 as defined in equation (3) is now applied to the clump weight. The horizontal off-target offset can be calculated as follow:

$$H = L.\sin\left(tan^{-1}\left(\frac{F_3}{m_c}\right)\right) \qquad (5)$$

Where H is the horizontal off-target offset

F_3 is the tether drag forces applied to the clump weight

m_c is the clump weight in water

L is the full tether length

Typically the currents through the water column are not uniform. Currents are typically stronger near the surface and lower or even null in deep waters. Assuming a MiniROV deployed in 950 m of water with an in water 50 kg clump weight and a current of 1 kt for the first 200 m, the calculations show the clump weight will be off-target by 60 m. In the same conditions with a 2 kt current instead of 1 kt, the off-target distance is 245 m. In both cases the ROV remains maneuverable, and a skilled captain may be able to compensate for the offset by adjusting the location of the ship.

The heavier the clump weight, the less it will be affected by the current. But most MiniROVs have small diameter tethers with about 100 kg working strength which significantly limits the maximum clump weight. In fact, in calm seas, if a clump weight of half the working load can safely be used, in heavier seas when the surface ship is subject to waves, the clump weight should not be more than one third of the tether working load to take into account momentary forces due to clump weight acceleration in the water. When heavier clump weights are required, it is possible to deploy the clump weight with an independent non-twist steel line and motorized winch such that the weight of the clump weight is not supported by the tether. This method is effective, but requires more equipment and adds additional challenges to the deployment and retrieval of the system.

2) Clump Weight Deployment and Retrieval Challenges

Deploying a MiniROV with a clump weight is cumbersome. The operator has to pay attention during deployment to prevent damaging the ROV due to collision with the clump weight. Non-motorized deployment of a clump weight requires at the very least one additional operator. The most common issue during deployment is entanglement of the free-section of tether with the section of the tether in tension. This may lead to restricted ROV motion, and/or tether damage.

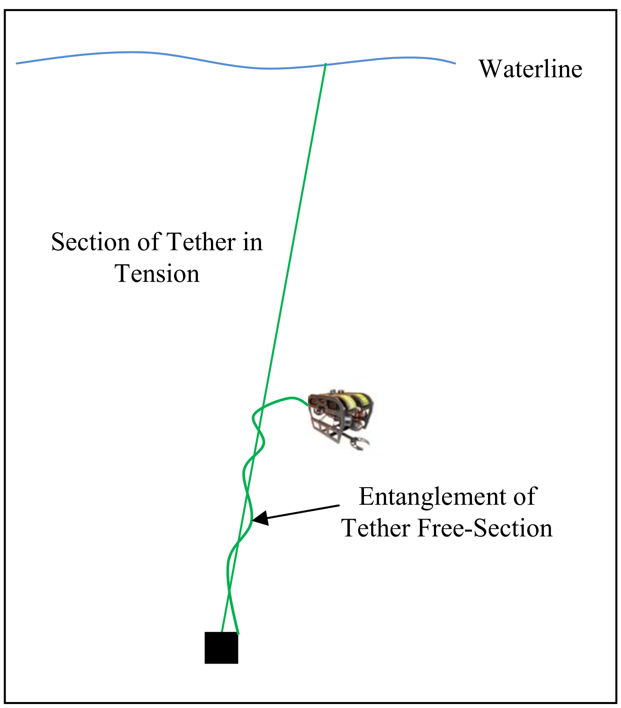

Fig. 9. Entanglement During Clump Weight Deployment.

Entanglement as shown on Fig. 9 is common when the descent of the ROV is not independent of the descent of the clump weight. If the clump weight descends first leading the ROV, and the free tether section pulls the ROV down, the ROV will come close to the section of tether in tension and the system will naturally wrap around itself. To avoid this, the ROV descent must be controlled by the operator away from the clump weight and away from the section of tether in tension. This is not an easy task especially for lengthy deployments in deep waters. Minor entanglement reduces the excursion capability of the ROV by making the effective free section of tether shorter. Major entanglement can lead to complete failure to operate the ROV due to tether damage.

3) Clump Weight and Ship's Heave

The vertical motion of the deployment ship with the swell is called heave. Because of the free section of tether between the clump weight and the ROV, the ROV is not subject to heave but the clump weight is. If the ROV, for any reason, is brought directly above or underneath the clump weight, the vertical motion of the relatively dense clump weight has a high risk of damaging the ROV. To prevent this risk, an active heave compensation system is required to limit the relative motion of the clump weight with respect to the ROV.

4) Shorter Excursion Capability with a Clump Weight

Theoretically, the section of tether between the clump weight and the ROV previously labeled free-section, can be long enough to provide the desired excursion radius capability around the clump weight. In reality, the risk of entanglement is higher the longer the free-section. To be manageable operators will typically keep the free section less than 25m leading to a much reduced excursion capability compared to a free swimming ROV operating in shallow water. In order to operate in currents and in deeper waters without reducing the excursion capability, a Tether Management System (TMS) is required.

III. Tether Management Systems (TMS)

A. Background

The TMS has been used for deployment of Work Class ROV (WROV) for many years. Not only does the TMS offer a solution to many of the issues described when using a clump weight system, they also provide a space to install large and heavy power conditioning components often necessary when using long cables required to operate in deeper waters. The most common types of TMS are top-hats and garages. The top-hat TMS receives the ROV from underneath the TMS frame. Typically the ROV is out in the open with the TMS directly above. The garage type TMS receives the ROV horizontally. The TMS in this configuration provides protection around the ROV. Both types are equally effective with their own set of pros and cons.

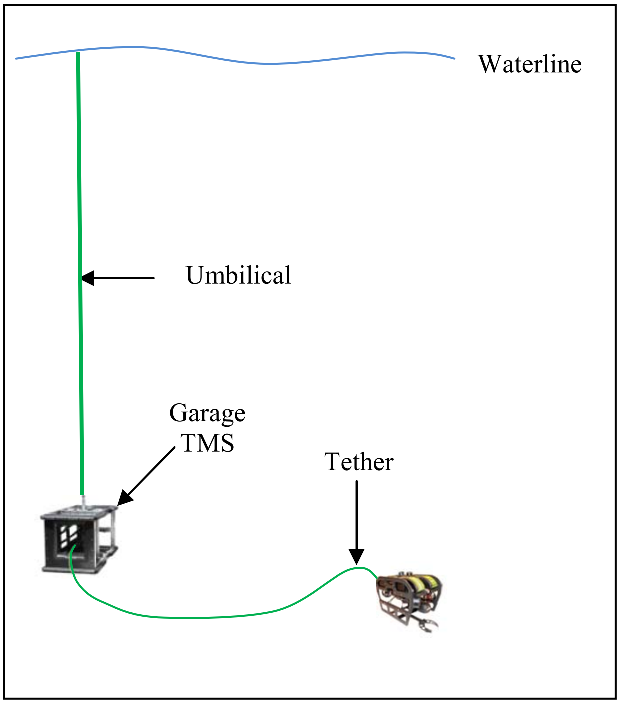

Fig. 10. Typical Garage TMS Configuration.

A typical TMS configuration as shown on Fig. 10 consists of a TMS deployed from a strength armored umbilical. A mechanism inside the TMS, consisting typically of an underwater winch, deploys the tether for the ROV excursion.

B. *Is the TMS an Effective Clump Weight?*

Yes, a TMS is an excellent clump weight. Because the TMS is supported by an armored umbilical, as opposed to a neutrally buoyant tether, weight can easily be added to the TMS to prevent the system from drifting in the current. In addition the TMS can include thrusters to maintain a particular orientation or to help stabilize the system for operation in higher currents. The main disadvantage of a clump weight is the fixed length section of free tether. The fixed tether length is limiting in terms of how far the ROV can reach. It is also what makes clump weight deployment challenging because the free section of tether is difficult to control and therefore entanglement is likely to happen during deployment. With the underwater winch located inside the TMS for tether deployment, the free section of tether is now adjustable remotely from the surface. For MiniROVs, instead of a typical 25m limit, the tether can now reach up to 200 m and provide excursion within a 400 m diameter circle around the TMS. During deployment, the ROV is in contact with the TMS with no free tether deployed. The TMS can travel several thousands of meters with no risk of tether entanglement.

C. *TMS Conclusions*

In conclusion, the TMS combines all the advantages of a clump weight while offering solutions to the short comings of using a clump weight. However, if MiniROVs are often deployed manually due to their light weight, deep water operation requiring a TMS makes manual deployment nearly impossible. A Launch and Recovery System (LARS) needs to be added to the system.

IV. Launch & Recovery System (LARS)

A. *Typical LARS*

A typical LARS consists of a support structure capable of moving the TMS and ROV arrangement from the deck to the water safely. The structure is semi-permanently installed on the surface ship and a motorized winch assists in the deployment of the ROV and TMS via the umbilical. Because of their large size and weight, WROV often use a large A-frame. The A-frame also includes a docking cone responsible for safely leading the TMS to a docking position for transport of the system on deck. When considering MiniROVs, a scaled down version of their big brothers the WROVs, it is easy to understand how the LARS, just like the ROV and the TMS scales down and requires much less volume and weight to provide the same function.

B. *LARS for MiniROVs*

For deep deployment of MiniROVs, the LARS is small enough to be integrated as part of a 20 foot shipping container. SeaBotix is using a section of a shipping container to provide space for a motorized winch as shown on Fig. 11. Near the ceiling of the container, a twin boom system is deployed outside of the container through double doors offering 3m of overboard reach. Mounted towards the end of the twin boom support structure is a hydraulically damped docking cone with 2 degrees of motion to help prevent umbilical wear when the TMS is deployed and the ship is pitching and rolling.

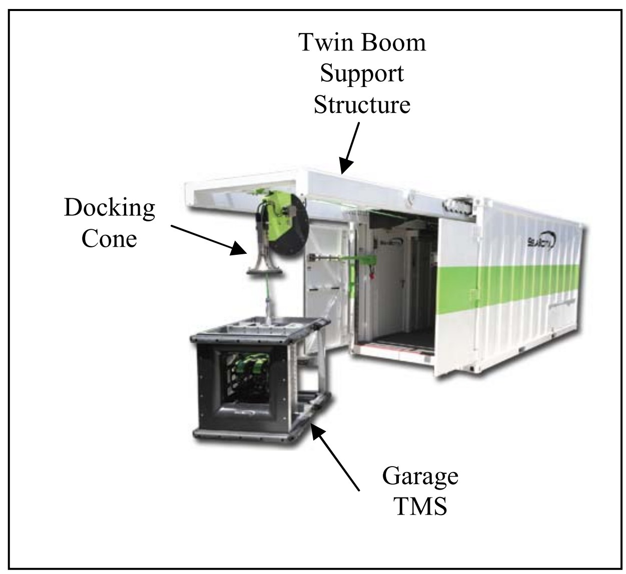

Fig. 11. SeaBotix MiniROV LARS.

When the support ship is heaving, the TMS would naturally move up and down while the ROV is deployed away from the TMS. This is problematic when trying to dock the ROV back in the TMS while the TMS is moving. A skilled operator typically waits for a quiet time in between a series of waves to dock the ROV while the heave is minimal. Alternatively, the winch system responsible for deploying the TMS can be outfitted with an active heave compensation module. A Motion Reference Unit (MRU) is installed on the ship to sense the heave motion. The information is fed to the winch software to automatically spool and un-spool umbilical as necessary to compensate for the motion of the ship and therefore keep the TMS stable with respect to the ROV. The benefit of active heave compensation is the ability to safely deploy and retrieve the ROV back to the TMS in higher sea states.

V. Conclusions

Historically, MiniROVs were designed for shallow water applications. More and more they are being used in deeper water. The limitations to take a MiniROV deeper is not the hardware depth rating, but rather the method to enable the ROV to be deployed safely and operate in currents while retaining full maneuverability. With no current, it is possible to free-swim a MiniROV down to 1000 m. Using a clump weight certainly is a cost effective solution for dealing with currents, however it significantly limits the effective operational area diameter. The elegant solution to deep water deployment (between 300 m and 4000 m) is the use of a Tether Management System (TMS) and its Launch & Recovery System (LARS). Most MiniROVs are deployed manually with un-motorized systems by one or two operators for shallow water applications. But for deep water applications, the weight of the TMS and long umbilical needs to be handled by a motorized winch and LARS. However, the size of the components for the LARS is still a fraction of the size and cost of the same components for a Work Class ROV. This allows fully integrated package with a small footprint such as the Containerized Delivery System (CDS) offered by SeaBotix.

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Clump weight handling information has been compiled using the return on experience from MiniROV expert operators such as Ronald J. Bernier (Advanced Remote Marine Services) and Mark L. Pidcoe (SeaBotix).

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Illustrations on Fig1, 4-11 created by SeaBotix.