# SUBMARINE RESCUE: RESEARCH ON RESCUE BELL APPARATUS.

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***Abstract.*** *In general, the submarine is a safe vehicle but, more than 170 submarines have been lost around the world last century. Collisions, fire, equipment failure, inadequate training and others reasons, all have had a part to play. So, several old and new rescue techniques have been developed, including the so called "rescue bell method". The aim of this paper is to develop a mathematical model of the complete system, in order to determine and simulate how tethers or umbilical cables can contribute with the dynamical behaviour of a rescue bell apparatus. In order to reproduce the disturbance effects during actual operation conditions, a model of the umbilical cable of the rescue bell is considered. The resulting model is then used to evaluate the performance of this rescue operation. This model will take part on a decision support system to access the feasibility of a submarine crew rescue mission, taking into account the actual environmental conditions during the operation.*

***Keywords****: Dynamical analysis; umbilical cables; Multibody System Dynamics; Kinematics*

## 1. INTRODUCTION

Just a few years ago, ships just sail on the sea surface, but after the invention of submarine vessel, the seabed could be exploited too. This equipment allows fighting with advantages in several warships, beyond to permit many civilian submarine exploitation missions.

The adaptations and techniques that allow people live for months or even years underwater are some of the most brilliant developments in naval science.

But, when a submarine goes down because of a collision with something or an onboard explosion a rescue mission is triggered. Depending upon the circumstances of the disaster, several techniques of “search and rescue” can be employed to solve this issue.

In general, a rescue vehicle is sent down to access the situation so the crew can be removed or if the disabled submarine is trapped or has lost electric power, the vehicle can often cut it free or tow it to the surface.

The main rescue vehicles used at these events are called **Deep-Sea Rescue Vehicles (DSRV)** that could descend and attach to sunken submarines and **Submarine Rescue Chambers (SRCs)** that are metal pods that can be attached, or mated, to a disabled submarine. This equipment is called **“Rescue Bell”** too.

The Rescue bell apparatus is the unique technique adopted in Brazil and suffers severe limitations in strong currents and when mating with a *submarine* that is *lying* at extreme *angles*.

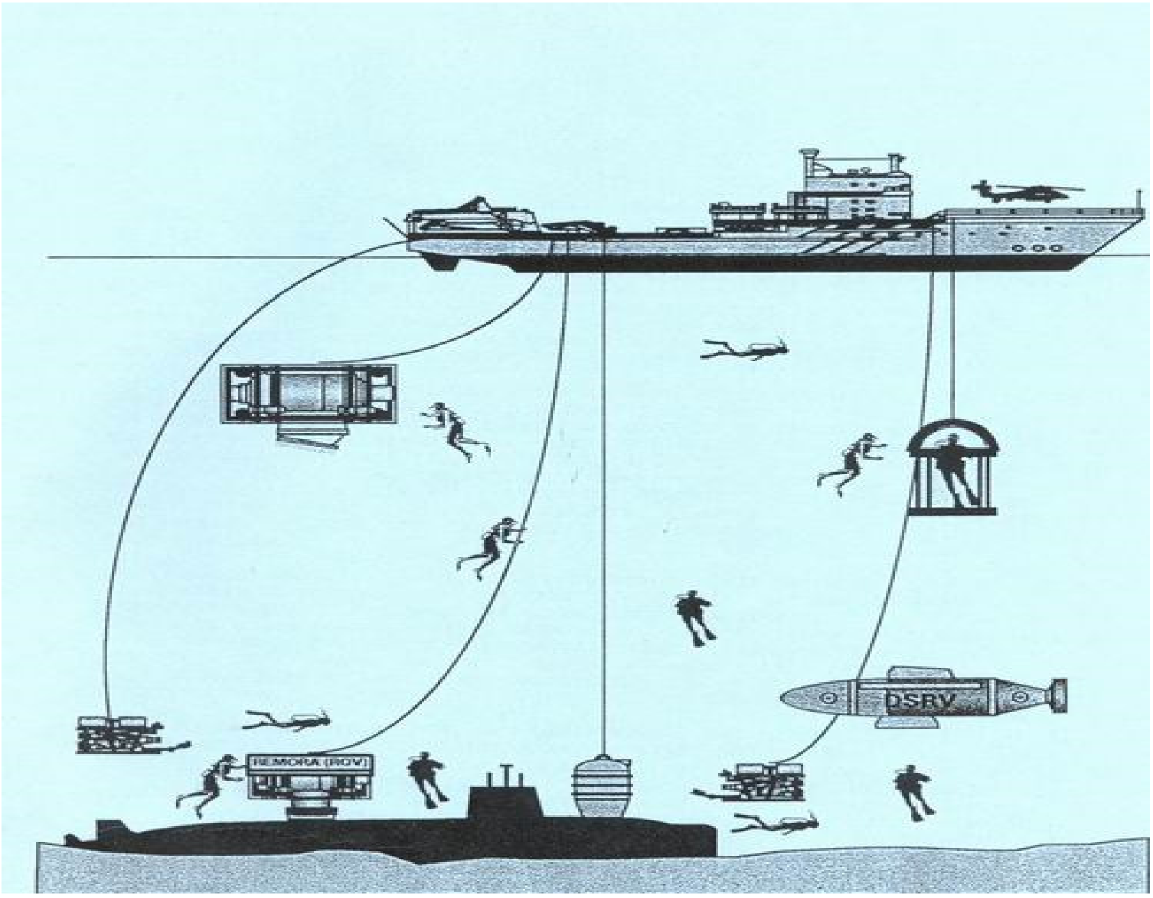


Figure 1 – Submarine rescue techniques

Nowadays, the Australian Submarine Rescue Vehicle (ASRV) REMORA is the best symbol of the state-of-art in rescue vehicles. It is a 16.5 tons machine built about a rescue bell and is capable of operations in excess of 500m in a current of 3 knots and of mating to a disable submarine lying at angles of up to 60° from the vertical.

The most of techniques presented in Figure 01, including the Brazilian and the Australian cases, consider that the vehicles are being towed. Vehicles which are towed have some similarities to the vehicles that have been discussed so far. For example, towed vehicles are often streamlined, and usually need a good directional stability. Some towed vehicles might have active lifting surfaces or thrusters for attitude control. On the other hand, if they are to be supported by a cable, towed vehicles may be quite heavy in water, and do not have to be self-propelled. The cable itself is an important factor in the behavior of the complete towed system, and in this paper, we concentrate our efforts on cable mechanics more than vehicle characteristics, which can generally be handled with the same tools as other vehicles, i.e., slender-body theory, wing theory, linearization, etc..

In general, cables can exceed 5000m in length, even a heavy steel cable. The cables are circular in cross section, and may carry power conductors and multiple communication channels. The extreme L/D ratio for these cables obviates any bending stiffness effects.

The classification of cable systems maybe made simply of the density of the cable. Light-tether (UMBILICALS) systems are characterized by neutrally-buoyant (or nearly so) cables, with either a minimal vehicle at the end, as in a towed array, or a vehicle capable of maneuvering itself, such as a remotely-operated vehicle (ROV).

An ROV operates at low speed, and must have actuators to control the tether if there are currents. Heavy systems, in contrast, employ a heavy cable and possibly a heavy weight; the rationale is that gravity will tend to keep the cable vertical and make the deployment robust against currents and towing speed. The heavy systems will generally transmit surface motions and tensions to the towed vehicle much more easily than light-tether systems.

Beyond this, it can be included considerations about environmental disturbance modeling such as:

- waves;
- current; and
- wind.

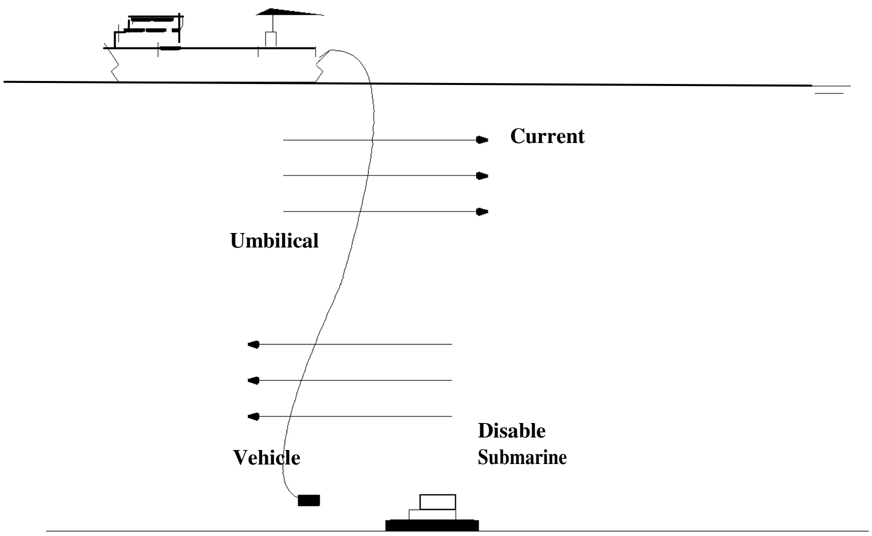


Figure 2 – Situation in focus

The situation in focus is about the use of vehicles for underwater rescue operations according figure 02. This is very difficult, in these conditions, by the fact that the traction exerted by long umbilicals causes relevant guidance and control problems. The umbilical's traction is in facts very difficult to be modeled **or** measured and, since it can change drastically and nonlinearly in response to movements of the vehicle-cable system.

In this paper we study a mathematical model of this disturbance.

## 2. A DYNAMICAL MODEL

A general nonlinear model of the dynamics of an underwater vehicle *can* be derived using either a Newtonian or Lagrangian formalism, regarding the vehicle as a six-degrees of freedom rigid body and representing the effects of the motion of the surrounding fluid as a generalized external force.

According Fossen (1994), the equation (1) represents the dynamical model of a submarine vehicle, where $M \in \mathbb{R}_{6X6}$ is the inertia and added inertia matrix, C(v) and D(v) are 6 **x** 6 matrices which, respectively, group together centripetal and Coriolis terms and contain the terms due to hydrodynamic damping forces, $\upsilon = [u, v, w, p, q, r]^T$ are the generalized velocities of the vehicle that is the three translational velocities and the three angular velocities in a body-fixed coordinate frame, $g(\eta)$ is a 6-dimensional vector which represent the gravitational and buoyancy force and $\tau_{RB} = [X, Y, Z, K, M, N]^T$ is a 6-dimensional vector which represent, the externally applied forces and torques in the body reference frame.

$$M\dot{\upsilon} + C(\upsilon)\upsilon + D(\upsilon)\upsilon + g(\eta) = \tau_{RB} \qquad (1)$$
$$\dot{\eta} = J(\eta)\upsilon$$

The matrix $J(\eta) \in \mathbb{R}_{6X6}$ defines the kinematic transformation between the body and the inertial frames, and depends only on the attitude parameters.

We can include in this equation a umbilical disturbance vector $\omega$ can be further expressed as $\omega$ = $D_1$d, where d$\in \mathbb{R}^3$ is the force exerted by the cable expressed in body coordinates and $D_1$ is a constant 6 by 3 matrix depending on the vehicle geometry.

## 3. UMBILICAL CABLE MODEL

The movement control of an underwater vehicle in all directions makes it an important skill in terms of rescue vehicle tasks. The umbilical cable that feeds it with energy and communication is designed such that the forces it exerts on the vehicle during rescue operation are minimal. So, it is generally neutrally buoyant and quite flexible in comparison to armored and heavy towing cables. However, McLain and Rock (1992) explain that the hydrodynamic and gravitational forces acting over the umbilical cable do create internal forces within the cable that disturb the motion of the vehicle.

The Rescue vehicle simulation has to model the umbilical cable dynamics, including a capability to simulate the case of slack state.

Young (1971) presented an analytical model of an underwater cable that uses a differential method to model the motion of a marine cable.

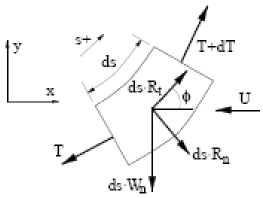


Figure 3 – Differential Method

For the configuration of a cable in a tow, he assumes that it is inextensible. Tension and hydrostatic pressure will elongate a cable, but the effect is a small part of the total length.

He employs the curvilinear axial coordinates that it has zero at the bottom end of the cable; upwards along the cable is the positive direction.

The diagram presented has the following terms:

- Wn: net in-water weight of the cable per unit length.
- Rn(s): external normal force, per unit length.
- Rt(s): external tangential force, per unit length.
- T(s): local tension.
- $\phi$ (s): local inclination angle.

Howell (1992) and Burgess (1993) showed that, by assuming negligible rotational inertia for the cable, additional forces could be included in the translational equations, thus simplifying a low-tension cable model. In this manner, the finite difference scheme could be extended to model the 2- dimensional motion of an umbilical cable in slack instances.

An alternative to this approach is the finite element method that defines the governing equations of motion over an element, or segment, of the cable. Driscoll et al. (2000) presented a 1-dimensional model of a marine cable composed of linear viscoelastic elements based on this approach.

A simple and effective cable model, consistent with the linear finite element approach, is the lumped-mass cable model that was first presented by Huang (1994). This model introduces the spatial discretization in the initial formulation of the governing motion equations by considering the cable to be a series of point masses, or nodes, connected by massless and viscoelastic elements. As shown by Huang (1994), the lumped-mass model reduces to a continuous cable in the case of infinitesimal element size.

To account for the elasticity of the cable, the tension within an element at any time step is calculated directly from the position of the element nodes using a constitutive relationship. As the element tensions are calculated explicitly, the onset of zero tension does not affect the stability of the lumped-mass method. However, the model results are highly unrealistic in slack or low-tension situations, and thus a motivation for the inclusion of bending effects in lumped-mass type models also exists.

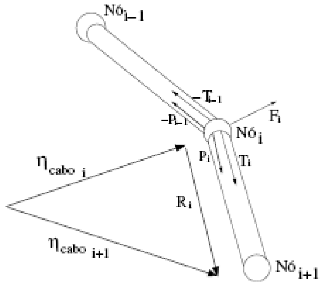


Figure 4 – Lumped Masses Method

The cable model used in this work is a lumped mass. In this model, the cable is discretized into a series of point mass elements connected by elastic springs. All external forces, like gravity and hydrodynamic drag, are lumped to the point masses. It allows the rapid determination of relative equilibrium configurations, which are used extensively during optimization of the system. The accuracy of such models has been validated for a variety of towing conditions. The major feature of the particular model used here is that the equations of motion are expressed in a mobile coordinate system attached to the vehicle. The cable takes up a relative equilibrium position when viewed from this frame. mass is also added to the lumped mass (or masses) closest to its position. The water density is assumed to follow the international standard and the drag coefficients of the cable are taken from.

This modeling does not consider that the torsion and flexion efforts are acting. So, the equation of motion can be represented by:

$$[M_i + M_{Ai}]_{cable}\ddot{\eta}_{cable} = (T_i + P_i)_{cable} - (T_{i-1} + P_{i-1})_{cable} + F_i \tag{2}$$

$\ddot{\eta}_{cable}$ is the acceleration of the *i*-knot and $M_i, M_{Ai} \in \mathbb{R}^{3x3}$ are the mass and added mass matrix of the *i*-cilindric element.

**3.1 Internal Forces**

As shown by Huang (1994), the lumped-mass model reduces to a continuous cable in the case of infinitesimal element size. Each discretized element can be modeled as a mass-spring-damper system:

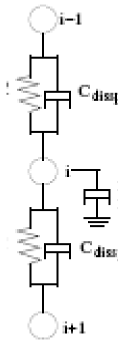


Figure 5 – Cable Model – Mass-spring-damper

At this configuration, the normal tension at *i*-knot can be expressed as:

$$T_{cable_i} = E\frac{A_{cable_i}}{l_{0_i}}R_i\left[1 - \frac{l_{0_i}}{|R_i|}\right] \tag{3}$$

| | |
|---|---|
| E | Young Modulus |
| $A_{cable}$ | Cross section ( $d_i$ ) |
| $l_{0_i}$ | Element length |

The variable $R_i$ is represented by:

$$R_i = (\eta_{cable_{i+1}} - \eta_{cable_i}) \tag{4}$$

$\eta_{cable_i}$ is the i-knot position.

Buckham, Nahon and Seto (1999) consider that the difference speed between cable´s two points is proportional and linear to the damper effect of these two points.

$$P_i = C_{cable}(\dot{\eta}_{s_i} - \dot{\eta}_{s_{i-1}}) \tag{5}$$

$\dot{\eta}_{s_i}$ is the *i*-knot speed at the s direction.

So, just only the cable tangent direction has non-null components and to transform these dissipation forces components in inertial coordinates, it's necessary project the speed vectors in "s" direction.

$$projection = \dot{\eta}_{cable_i} \frac{R_i}{|R_i|} \tag{6}$$

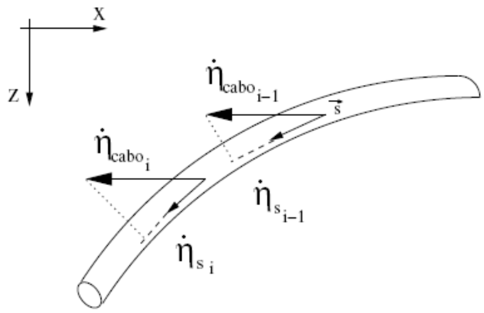


Figure 6 – Speed components

The speed component of tangent direction for each knot is obtained multiplying the scalar number "projection" by the tangent versor:

$$P_i = C_{cable}\left[\left(\dot{\eta}_{cable_i} - \dot{\eta}_{cable_{i-1}}\right)\frac{R_i}{|R_i|}\right]\frac{R_i}{|R_i|};$$

$$P_i = C_{cable}\frac{\left[\left(\dot{\eta}_{cable_i} - \dot{\eta}_{cable_{i-1}}\right)R_i\right]R_i}{|R_i|^2};$$

$$P_i = C_{cable}(\dot{\eta}_{s_i} - \dot{\eta}_{s_{i-1}}) \tag{7}$$

### 3.2 External Forces

The external force F is the result of the restorative forces $F_G$ and hydrodynamic drag efforts $F_F$

$$F_i = \frac{1}{2}(F_{F_i} + F_{F_{i-1}}) + F_{G_i} \tag{8}$$

The hydrodynamic force $F_F$ has two components (tangential and normal) expressed by:

$$F_{Fi} = F_{ni} + F_{t_i} = \frac{1}{2}\rho d_i (C_n + U_{ni}|U_{ni}| + C_t U_t |U_{ti}|)|R_i| \tag{9}$$

$\rho$ is the water specific mass;

$C_n$ and $C_t$ are drag coefficients; and

$U$ are components of fluid flow speed.

The lift forces did not be included in this calculation. Yamaguchi et al. (2001) has an example of calculation with these forces.

### 3.3 Simulation and Results

Considering the following parameters below:

$$\eta_{1final} = [50;50;30]m$$

$$\eta_{2final} = [0;0;1.3]rad$$

$$\dot{\eta} = [0.5m/s;0.5m/s;0.3m/s;0;0;0.013rad/s]$$

$$\dot{\eta}_{1_c} = [-0.5;-0.4;-0.1]m/s$$

And the umbilical cable physical parameters (Nomoto and Hattori, 1986):

- Cable length: 220m;
- cable diameter: 30 mm;
- Young Modulus: 1.372 x $10^{10}$ N/m2;
- Internal damper constant:100 Ns/m;
- Number of elements : 40 ; and
- Operation: 200m.

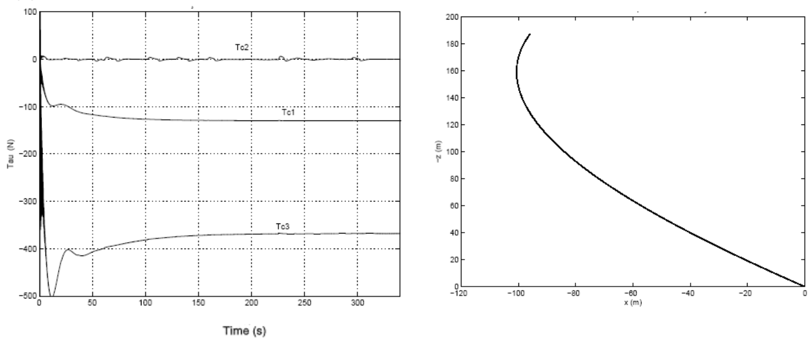


Figure 7 – Umbilical cable efforts and cable profile on "*xz*" plan after 350 s of simulation

### 3.4 Conclusion

This paper presented a mathematical cable model that will be used as a part of a rescue submarine model. The modeling technique called "lumped masses" was used. The cable was discretized as a set of small cilinders with lumped masses at its ends called knots.

The simulation has been confirmed Mullarkey, McNamara and O'Sullivan, 1999 that comment about the length reduction of cylindrical elements when the cable curvature is relevant. Once again, the simulation was checked with analytical results discussed about bidimensional case in Pode, 1951, and was considered similar.

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