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Design of a supervisory fuzzy logic controller for monitoring the inflow and purging of gas through lift bags for a safe and viable salvaging operation

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ABSTRACT

This paper presents a mathematical model and numerical time-domain approach to simulate the dynamics of a sunken ship/vessel being raised from seafloor by buoyancy (gas-inflating) systems in a form which is suitable for integrating control techniques to ensure hydrodynamic stability for a safe and viable salvaging operation. According to the two-degree-of-freedom equations of rigid-body vessel motion in diving plane, a conventional sliding mode controller is designed as the primary controller to regulate flow rate of filling gas inside the lift bags and a PID controller is designed as the secondary controller for regulating the purging of gas through the valves fitted on lift bags. Then a supervisory fuzzy logic controller is designed to monitor or switch between the primary and secondary controllers based on the buoyancy requirement. From the simulation studies, it is found that the supervisory fuzzy logic controller is capable to maintain hydrodynamic stability by suitably defining the linguistic fuzzy rules, which is created based on the author's experience in conducting numerical simulation using primary and secondary controllers.

1. Introduction

Marine salvage is an operation of rescuing a ship/vessel, its cargo or other properties from impending peril. The salvage comprises of towing and refloating a sunken or stranded vessel with the main purposes to prevent the marine environment from the pollution and to clear a channel for the navigation. Ships sink or capsize because they lose their buoyancy or stability due to the collision, battle or weather damage, flooding and other means. The rescue of a damaged vessel is a very difficult task when compared to an intact ship in the same location. Salvaging of sunken ships requires both the recovery of sufficient buoyancy to bring the ship afloat and the suitable buoyancy distribution to regain the satisfactory condition of stability, trim and strength (U.S.Navy, 2006). There are three methods commonly used in the marine salvage industry to extract the sunken objects from the sea bottom, i.e. by using the floating cranes, the Remotely Operated Vehicles (ROVs) and the buoyancy systems. Floating cranes can be used for water depths of 2000 m with a good controllability; however the weight of cables becomes more than that of the payload for deeper lifts and hence the process becomes awkward and costly. As the cranes are fitted onto a moving vessel, there will be the operational constraints due to the limiting sea state affected by weather conditions. Excessive cost of hiring and the limited availability of cranes are the major problems facing the salvage industry. ROVs, on the other hand, can be used in higher water depths and they are highly controllable. Nevertheless, they can be only used for lifting smaller objects as the lifting capacity is limited by the size and power of the thrusters used for the propulsion (Nicholls-Lee et al., 2009). Buoyancy systems have the advantage that they can be used for lifting any size of objects from any depth with comparatively less costs.

The concept of using buoyancy systems (e.g. the gas inflated bags) for salvaging sunken vessels from the deep ocean has been around for centuries. This operation is based on the well-known ‘Archimedes’ principle for which the force on the object can be determined by subtracting the weight of the object in air from the weight of the fluid displaced by that object (Farrell, 2008; Rawson and Tupper, 2001). In general, the bottoms of inflatable bags are attached to the payload to be lifted and inflated using pipes from the gas generating system. In salvage industry, there are mainly two types of lift bags available for recovering sunken objects; one is parachute type and the other is cylindrical type. Parachute type bags are generally preferred for lifting purpose, whereas cylindrical type lift bags are used for providing stability (JW Automarine, 2010; Subsalve, 2010).

The main drawback of using the inflating bags for marine salvage operation is due to the difficulty in controlling the vertical speed and pitch motion as the ship ascends. Due to the suction break out force, a

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large buoyancy force may be initially required to separate the ship from the seabed, resulting in an excessive vertical speed and pitch angle after break out. During the ascent, any trapped air inside the hull may also expand and further increase the buoyancy. Also due to the pressure difference between gas inside the lift bag and surrounding sea water pressure in accordance with the decrease in water depth during the ascent, the gas inside the lift bag expands. All these factors lead to an increase in buoyancy force and hence result in an excessive vertical speed as well as pitch angle during the ascend. Excessive vertical speed results in a potentially-hazardous working environment to divers and salvaging crews and this may cause the lift bag to reach the surface of the water so fast that the air escapes from the bottom. High values of pitch angle cause the lift slings to break loose from payload and hence results to a further buoyancy loss. All these factors make the payload to sink back to the bottom which, in turn, results in a loss of time, damage to the hull, high operating and maintenance costs, and risk to divers and crew members (Farrell, 2008; JW Automarine, 2010; SuSy, 2011).

Hence, in order to ensure hydrodynamic and structural stability during the ascent, it is proposed to design three control systems; a primary controller for regulating the flow rate of filling gas inside the lift bags according to the buoyancy requirement based on the hydrostatic force due to weight, buoyancy and suction breakout, hydrodynamic force and uncertainty due to external disturbances. A secondary controller to regulate the opening of a purge valve fitted on the lift bags in accordance with the excess buoyancy available after suction breakout and the variation in pressure difference between the gas inside the lift bags and surrounding seawater. Then a supervisory controller needs to be designed to monitor or switch between the primary and secondary controller according to the depth error and ascent rate.

In Section 2, the dynamic equations of rigid-body motion describing a raising sunken vessel are formulated in a state-space form and then purge valve modeling is carried out. In Section 3, a conventional sliding mode-depth controller is designed as the primary controller to regulate the gas inflating flow rate based on the state space model. A secondary PID purge valve controller is also designed and finally a supervisory fuzzy logic controller is proposed to monitor the primary and secondary controllers. Numerical simulation results based on a pontoon experimental model are discussed in Section 4. The paper ends with the conclusions in Section 5.

2. Problem formulation

Ship calculations for the salvage operation are typically less detailed than those in the preliminary design, which depends on the available information pertaining to a particular ship scenario. A number of assumptions are usually required to simplify the problem. Forces acting on a sunken vessel consist of hydrostatic (i.e. weight, buoyancy and suction breakout force) and hydrodynamic components. The variation of hydrodynamic forces with velocities, accelerations and control surface deflections are expressed in terms of hydrodynamic coefficients. These coefficients can be derived from physical model tests or theory, the number of coefficients used being subject to the amount of data available, past experience etc. The most significant task in this paper is how to model the salvage dynamics in a form which is suitable for integrating control techniques to ensure hydrodynamic stability during the ascent. Due to the coupled nature of salvage dynamics and to integrate controller techniques, the mathematical modeling is carried out as two subsystems. In the primary model, the salvage dynamics is formulated in such a way that the variation in additional buoyancy due to flow rate of filling gas inside the lift bags is the controlling force with respect to hydrostatic force due to weight, buoyancy and suction break out, hydrodynamic forces and uncertainty arises due to external disturbances. In the secondary model, the purging of gas through the valve is taken as the control parameter by accounting the excess buoyancy available after suction break out and to the variation in pressure difference between gas inside lift bag and surrounding sea water pressure for a stable ascent. The purpose of the simulation system is to bring the vessel with the lift bags just below the surface by the supervisory controller and towed to the nearby port.

2.1. Primary model of a raising vessel

To describe the motion of a raising vessel, two reference frames are considered as seen in Fig. 1, including the earth- and body-fixed frames. The origin of the body-fixed frame coincides with the centre of gravity (C_g) of the vessel being in the principal plane of symmetry. The origin of the earth-fixed coordinate system is considered to be fixed at sea bottom. The positions and orientations of the vessel (kinematic variables) are expressed with respect to the earth-fixed coordinates whereas

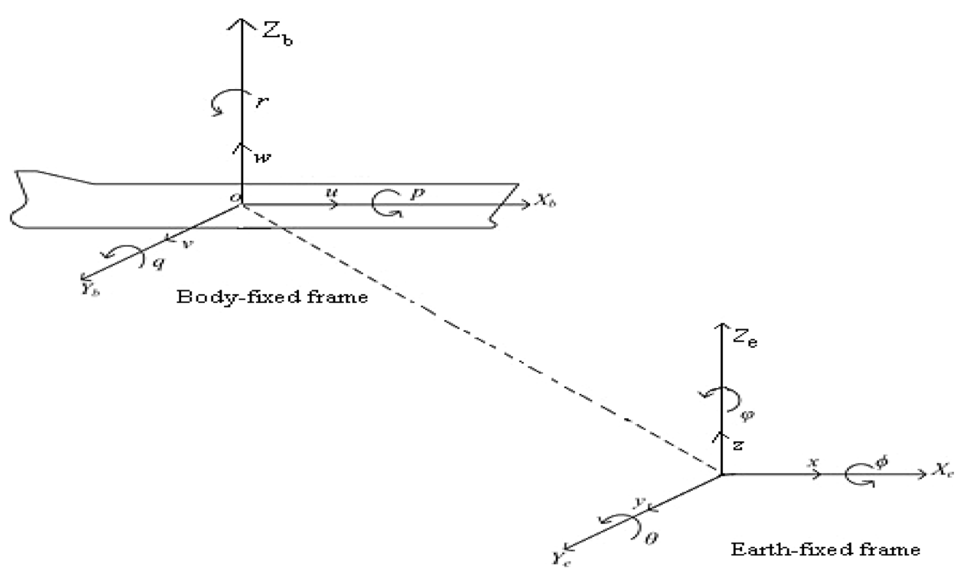

Fig. 1. Vessel model and reference coordinates (Fossen, 1994, 2002).

the linear and angular velocities of the vessel (dynamic variables) are expressed in the body-fixed coordinates. The transformation between the two coordinate systems is done by using Euler angles (Φ, θ, ψ) or by using kinematic relations (Fossen, 1994, 2002; Healey and Lienard, 1993).

To describe the dynamics of the sunken vessel ascending from the seafloor, it is preliminarily assumed that:

- the vessel behaves as a rigid body
- the acceleration of a point on the surface of the earth is neglected,
- the external loads comprise of the breakout, hydrostatic and hydrodynamic forces, and the seabed is flat creating a total lift force of 1.3 times the ship wet weight (Sawicki and Mierczynski, 2003; Vaudrey, 1972).

2.1.1. Equations of vessel motion

As the problem is concerned with the dynamics of raising sunken vessels (i.e. the control surfaces are inactive and the depth control is by regulating the additional buoyancy provided by the inflating system), it is further assumed to consider only the diving or vertical-plane (surge, heave and pitch) motions in the stability analysis. However, the surge equation couples with heave and pitch, through the meta-centric height. This dynamic coupling could be eliminated by redefining hydrodynamic coefficients with respect to the ship's Cg instead of its geometric centre (Cristi et al., 1990; Healey and Macro, 1992). For a sunken vessel, it is also known that the forward speed is zero. However, due to external forces such as currents, the surge motion may exist, which can be considered as an external disturbance to the system. As an adaptive non linear controller can effectively handle system modeling errors, external disturbances and uncertainty and thereby maintain hydrodynamic stability in diving plane, so that in this study, we discard the surge terms in the development of equation of motion (Velayudhan et al., 2011). Thus, the system model variables include the heave velocity (w), pitch angle (θ), pitch rate (q) and global depth position from sea bottom (z).

The equations of motion presented here are the core of the simulation program in MATLAB & SIMULINK. These equations, using body axes variables are solved for the motions in diving plane. These variables are then transformed to the earth–fixed coordinates using the kinematic relations (i.e. by Euler angles) (Fossen, 1994, 2002). The system is then placed in state space form so that state space model can be formed simply by assigning states to the associated variables.

According to Newton – Euler approach, the equations of motion for heave and pitch are (Fossen, 1994):

$$m(\dot{w} - x_G\dot{q} - z_G q^2) = Z \tag{1}$$

$$I_{yy}\dot{q} + m[z_G(wq) - x_G\dot{w}] = M \tag{2}$$

where, m is the vessel mass, I_{yy} the mass moment of inertia, x_G, z_G the coordinates of the centre of gravity in X_b and Z_b directions respectively, Z the heave force and M the pitch moment.

The right hand side of the above equations consists of hydrostatic, hydrodynamic, break out and control force components.

2.1.1.1. Hydrostatic force and moment. Hydrostatic force and moments are due to the vessel weight W and buoyancy B. The buoyancy of the sunken vessel may be changed due to the sea density variation and to the compressibility of the hull, which can be accounted by considering a linear change in volume with depth.

Therefore, the buoyancy force provided by the sea water is given by (Faltinsen, 1990):

$$B = \rho\nabla g + \mu z(\rho/\rho_o) \tag{3}$$

In which μ is the increase in buoyancy per unit increase in depth in sea water of standard density ρ_o, ρ the actual density of surrounding sea, ∇ the volumetric form displacement, g the gravitational acceleration and z the vertical coordinate position or depth from sea bottom.

The net hydrostatic force in the inertial coordinate system is *(B-W)* in the positive Z direction (upwards) (i.e. buoyancy is taken as positive and gravity is negative). Therefore, in the body-fixed coordinate system, the hydrostatic components of force and moments for heave/pitch motions are (Fossen, 1994, 2002):

$$Z_{hs} = (B - W)\cos\theta \tag{4}$$

$$M_{hs} = -(z_B B - z_G W)\sin\theta - (x_B B - x_G W)\cos\theta \tag{5}$$

where θ is the pitch angle and x_B, z_B are the coordinates of the centre of buoyancy in X_b and Z_b directions respectively.

2.1.1.2. Hydrodynamic force and moment. The hydrodynamic components of force and moment for heave/pitch motions are (Fossen, 1994; Healey and Lienard, 1993; Beyazay, 1999; Keller, 2002):

$$Z_{hd} = Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} + Z_w w + Z_q q \tag{6}$$

$$M_{hd} = M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} + M_w w + M_q q \tag{7}$$

where,

$$Z_{\dot{w}} = \tfrac{1}{2}\rho l^3 (Z'_{\dot{w}}),\ Z_{\dot{q}} = \tfrac{1}{2}\rho l^4 (Z'_{\dot{q}}),\ Z_w = \tfrac{1}{2}\rho l^2 (Z'_w),\ Z_q = \tfrac{1}{2}\rho l^3 (Z'_q),$$
$$M_{\dot{w}} = \tfrac{1}{2}\rho l^4 (M'_{\dot{w}}),\ M_{\dot{q}} = \tfrac{1}{2}\rho l^5 (M'_{\dot{q}}),\ M_w = \tfrac{1}{2}\rho l^3 (M'_w),\ M_q = \tfrac{1}{2}\rho l^4 (M'_q) \tag{8}$$

in which $Z'_{\dot{w}}$ the non dimensional added mass coefficient in heave, $Z'_{\dot{q}}$ the non dimensional added mass coefficient in pitch, Z'_w & $Z'_{\dot{q}}$ are the non dimensional heave force coefficients induced by angle of attack, $M'_{\dot{w}}$ the non dimensional added mass moment of inertia coefficient in heave, $M'_{\dot{q}}$ the non dimensional added mass moment of inertia coefficient in pitch, $M'_{\dot{w}}$ & $M'_{\dot{q}}$ are the non dimensional pitch moment coefficients from heave and pitch respectively and l is the length of the vessel. Forces and moments due to external disturbances such as wind, current etc that creates uncertainty during the marine salvage operation are also to be accounted during the controller design.

2.1.1.3. Breakout force. The breakout or suction force (R) accounts for the difference between the total lift force required (F) and the object's wet weight (G = *W-B*). It is theoretically and empirically difficult to estimate this breakout force due to the involvement of several variables and unknowns (U.S. Navy, 2006). In general, the amount of breakout force & estimation of break out time depends on the seafloor soil characteristics (i.e. the compressibility of soil skeleton and pore water, permeability etc.), the embedment depth and time, the object shape parameters and the loading conditions. The total lift force (F) required for the complete extraction of the object from the sea bottom should be greater than their submerged weight (G) due to the ground reaction (R) exerted by the soil (see Fig. 2) (Foda, 1982; Mei et al., 1985; Sawicki and Mierczynski, 2003).

Sawicki and Mierczynski (2003) proposed a simple formula for the estimation of total lift force as:

$$F = G + R = (1 + k_p)*G \tag{9}$$

where k_p is an empirical coefficient depending on the nature of subsoil and its values are given as (Sawicki and Mierczynski, 2003):

$$k_p = \begin{cases} 0.05 - 0.1 & \text{coarse} \quad \text{sand} \\ 0.15 - 0.20 & \text{fine} \quad \text{sand} \\ 0.25 - 0.45 & \text{clayey} \quad \text{bottom} \end{cases} \tag{10}$$

Vaudrey (1972) investigated the efficacy of 3 analytical methods (i.e. Muga, Liu and Lee methods) for the prediction of breakout forces with different object shapes such as a cylinder, sphere and block, with and without breakout force reduction techniques. From the analysis, it was observed that the use of breakout reduction methods such as the mud suction tubes, water flooding and air jetting would reduce the total lift force by approximately 15% and eliminate the snap loading condition. The selection of breakout reduction methods depends on the

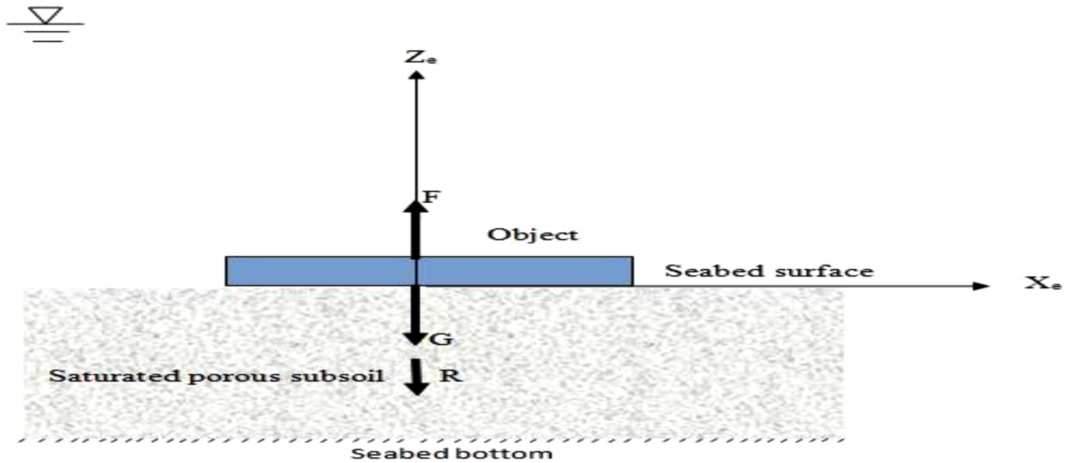

Fig. 2. Lift force model to extract an object from the seabed (Sawicki and Mierczynski, 2003).

particular salvage operation, bottom soil conditions and the availability of equipments. From the above literature (Sawicki and Mierczynski, 2003; Vaudrey, 1972), the total lift force is assumed to be 1.3 times the wet weight of the vessel. Break out time can be calculated based on the work of Mei et al. (1985) & Foda (1982). Note that the break out component of suction lift force is only 0.3 times the wet weight in the negative Z direction.

Therefore, heave component of break out suction force in body fixed coordinate system (i.e. in positive Z direction) can be written as:

$$Z_{suction} = 0.3\,(B - W)\cos\theta \tag{11}$$

Similarly, pitch component of break out suction force in body fixed frame can be written as:

$$M_{suction} = 0.3*[-(z_B B - z_G W)\sin\theta - (x_B B - x_G W)\cos\theta] \tag{12}$$

2.1.1.4. Control force: additional buoyancy provided by the inflating system. For the sunken vessel resting on the seafloor, the vessel weight is balanced by both the buoyancy and the ground reaction. Additional force required to lift the vessel should overcome both the in-water object weight and the ground reaction. This force, described in terms of the buoyancy, could be provided by the volume of gas inside the lift bags. The gas-generating system (solid, liquid or cryogenic pressurised system) is used such that the produced gas is pumped into the lift bags at a desired flow rate using pipes for a stable ascent.

The variation of volume with respect to time is the control parameter:

$$u_c = V(t) \tag{13}$$

Consequently, the additional buoyancy provided by the lift bags can be written as:

$$B_a = (\rho - \rho_g)gV \tag{14}$$

where ρ_g is the density of gas inside the lift bag. The components of additional buoyancy for heave mode in body fixed frame can be written as:

$$B_{ah} = (\rho - \rho_g)gV\cos\theta \tag{15}$$

Similarly, the components of additional buoyancy for the pitch mode can be written as:

$$B_{ap} = -z_B(\rho - \rho_g)gV\sin\theta - x_B(\rho - \rho_g)gV\cos\theta \tag{16}$$

2.1.2. Kinematic relations

The kinematic relations are used to transform the motion variables from local to global coordinate systems. The kinematic relations for heave and pitch can be obtained from Fossen (1994) and Fossen (2002):

The simplified kinematic relations for heave and pitch motions are (u, v, p, r, $\Phi = 0$):

$$\dot{z} = w\cos\theta \tag{17}$$

$$\dot{\theta} = q \tag{18}$$

2.1.3. Development of state-space model

For small values of pitch angle, it is assumed that $\sin\theta = \theta$ and $\cos\theta = 1$. Imposing linearization about an equilibrium point (i.e. discarding q^2 term) and neglecting the products of small motions or coupled terms (i.e. neglecting wq term), the equations of motion for heave and pitch mode can be written in the state-space matrix form as:

$$\begin{bmatrix} -mx_G - Z_{\dot{q}} & 0 & m - Z_{\dot{w}} & 0 \\ I_{yy} - M_{\dot{q}} & 0 & -mx_G - M_{\dot{w}} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{q} \\ \dot{\theta} \\ \dot{w} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} Z_q & 0 & Z_w & 0 \\ M_q & -1.3*(z_B B - z_G W) & M_w & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} q \\ \theta \\ w \\ z \end{bmatrix} + \begin{bmatrix} (\rho - \rho_g)*g \\ -(\rho - \rho_g)*g*x_B \\ 0 \\ 0 \end{bmatrix} [V(t)] \tag{19}$$

which has the form,

$$[M_0]\{\dot{x}_s\} = [A_0]\{x_s\} + [B_0]\{u_c\} \tag{20}$$

where,

$$[M_0] = \begin{bmatrix} -mx_G - Z_{\dot{q}} & 0 & m - Z_{\dot{w}} & 0 \\ I_{yy} - M_{\dot{q}} & 0 & -mx_G - M_{\dot{w}} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{21}$$

$$[A_0] = \begin{bmatrix} Z_q & 0 & Z_w & 0 \\ M_q & -1.3*(z_B B - z_G W) & M_w & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \tag{22}$$

$$\{B_0\} = \begin{bmatrix} (\rho - \rho_g)*g \\ -(\rho - \rho_g)*g*x_B \\ 0 \\ 0 \end{bmatrix} \tag{23}$$

$$\{x_s\} = \begin{bmatrix} q \\ \theta \\ w \\ z \end{bmatrix} \tag{24}$$

$$u_c = V(t) \tag{25}$$

where x_s is the state vector and u_c is the control vector.

Eq. (20) can be reduced in the form,

$$\{\dot{x}_S\} = [A]\{x_S\} + [B]\{u_C\} \tag{26}$$

which is the State Dependant Riccati Equation (SDRE), in which [A] is the system matrix and [B] is the input matrix, which are given by

$$[A] = [M_0]^{-1}[A_0],\ \ [B] = [M_0]^{-1}[B_0] \tag{27}$$

2.2. Secondary model: automated purge valve modeling

According to section 2.1.1.3, the lift force required to extract an object from sea bottom is typically about 1.3 times the wet weight. This implies that, soon after the suction break out, excessive buoyancy is present within the lift bags that cause a sudden increase in vertical speed. Also, during the ascent through water column, the lift bags experience a decrease in pressure with respect to the variation in depth. This decrease in pressure causes the volume of gas inside the lift bags to expand, resulting in an increase in buoyant force (Farrell, 2008; J W Automarine, 2010; Subsalve, 2010). The automated purge valve is designed to eliminate the vertical acceleration experienced by the lift bags during the ascent by restricting the expansion of gas through the valves. As the lift bag ascends, the expanded gas is purged through the valve in a controlled manner to compensate for gas expansion by which, constant buoyancy can be always maintained. A microprocessor can be used to sample the pressure at predetermined intervals by which the change in pressure over each interval can be calculated, which is then interpolated by a PID control algorithm to find the ascent velocity and then the actual depth. Opening or closing of valves are carried out accordingly with system commands that will alter the amount of gas purged (Farrell and Wood, 2009). Purge valve modeling is carried out according to Farrell (2008) and go through it for more details.

3. Controller design

3.1. Design of primary controller

For a complex under water nonlinear operation like marine salvage involving uncertainty and external disturbances, it is not possible to completely describe the system dynamics in a mathematical form. Due to the coupled nature of underwater dynamics, it is really difficult to design a control system fully based on the developed mathematical equations. Therefore the remaining possibility is to decouple the system dynamics based on some suitable assumptions and design a control system, which is capable of handling non linearity, system modeling errors, insensitiveness to parameter variations (i.e. mainly variation in hydrodynamic coefficients and suction breakout force) and external disturbance etc. The function of the primary controller is to regulate the flow rate of filling gas inside the lift bags according to the buoyancy requirement in accordance with the hydrostatic force due to weight, buoyancy and suction breakout, hydrodynamic forces and uncertainty arises due to external disturbance such as wind, current or voyage etc for a safe and viable salvage operation. Therefore the relative effectiveness of various control systems as a primary controller for regulating the gas flow rate is investigated and sliding mode controller is found to be optimum choice among the conventional controllers (Velayudhan, 2014).

Note that in this section there is also an active but not optimized purge gas controller. This results in the primary controller feeding gas into the lift bags whilst the purge controller is releasing gas. This is overcome by having a supervisory controller, over the primary inlet and secondary purge controllers, as described in Section 3.3.

3.1.1. Conventional sliding mode controller (CSMC)

A sliding mode controller (SMC) is selected as the primary controller for regulating the flow rate of filling gas inside the lift bags in order to maintain the stability of the raising vessel within the diving plane. This selection was made due to the following reasons (Healey and Macro, 1992; Healey and Lienard, 1993; Slotine and Li, 1991; Beyazay, 1999; Keller, 2002):

- SMC compensates for nonlinear behaviours
- SMC provides robustness to uncertainty
- SMC is straightforward to implement

In a closed loop control system, the function of the controller is to make the state variable x_s follow the desired state x_d with a prescribed dynamic characteristic in the presence of uncertainty and disturbances. The state variable error is defined as $e = x_s$-x_d. In the development of sliding mode controller, a sliding surface *(σ)* is to be created from a linear combination of the state variable errors such as position, velocity and acceleration. The aim is to drive the system to the sliding surface and ultimately to the condition $\sigma = 0$ while making sure that the state variables are always reducing (Slotine and Li, 1991; Healey and Lienard, 1993; Healey and Macro, 1992; Mcgookin, 1997). Therefore, sliding surface σ can be defined for a second order system as: $\sigma = \lambda e + \dot{e}$, where λ is the slope of the sliding surface. Then, the Lypunov method can be used to formulate the control law (u_c), which is obtained as (Velayudhan et al., 2012):

$$u_C = -[s^TB]^{-1}s^TAx_S - [s^TB]^{-1}\eta sat\left(\sigma/\Phi_b\right) \tag{28}$$

where $s^Tx_s = \sigma\ (x_s)$ is the weighted sum of errors in the state x_s, s is the right eigen-vector of the desired closed loop system matrix, and Φ_b is the boundary layer thickness. η is an arbitrary positive quantity provided to satisfy the Lypunov stability condition. The values of A and B can be obtained from Eq. (27). Let $k = [s^TB]^{-1}s^TA$, then the above equation becomes:

$$u_C = -kx_S - [s^TB]^{-1}\eta sat\left(\sigma/\Phi_b\right) \tag{29}$$

The gain vector k can be calculated in MATLAB using the pole placement method.

3.2. Design of secondary controller

In this section a secondary controller is proposed to regulate the area of purge valve opening fitted with lift bags in accordance with the excess buoyancy available after suction breakout and according to the variation in pressure difference between the gas inside the lift bags and surrounding sea water for a stable ascent. A PID controller is selected as the secondary controller to regulate the purge valve opening as explained in Farrell (2008).

3.3. Design of supervisory controller

For maintaining hydrodynamic stability in a salvage operation using buoyant systems, a SMC is the preferred choice as the primary controller for regulating the flow rate of filling gas inside the lift bags and a PID controller is chosen as the secondary controller to regulate the purging of gas through the valves fitted on the lift bags. Now for a safe and stable salvage operation, it is required to monitor or switch between these two sub controllers by a supervisory controller as per the depth error and depth rate. In such situations, the remaining possibility is to choose an intelligent controller such as fuzzy logic controller (FLC) as the supervisory controller for monitoring the primary and secondary controllers as shown in Fig. 3.

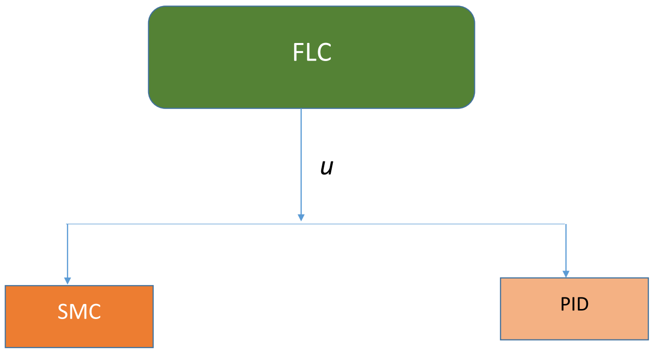

Fig. 3. Supervisory fuzzy logic controller.

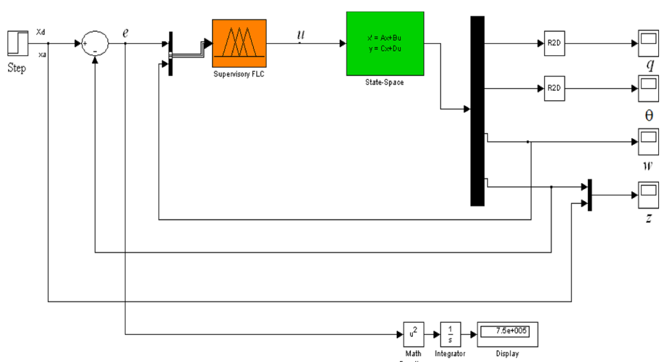

Fig. 4. SIMULINK block diagram of a supervisory FLC for marine salvage.

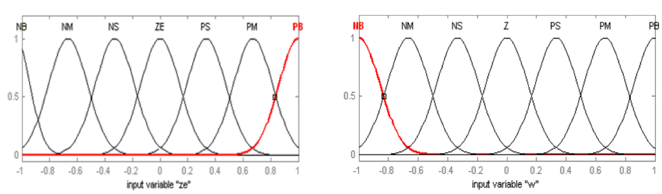

Fig. 5. (a): Membership functions for the input variable 'z_e' Fig. 5(b): Membership functions for the input variable w.

Based on the experience learned while conducting numerical simulations on primary and secondary controllers, a supervisory fuzzy logic controller is designed by utilizing MATLAB Fuzzy Logic toolbox and integrated in SIMULINK as shown in Fig. 4. Here inputs to the FLC are the depth error (z_e) and depth rate (w). The output or control variable is 'u' which regulates the buoyancy with respect to the depth error and depth rate. Depth error is defined as the commanded depth

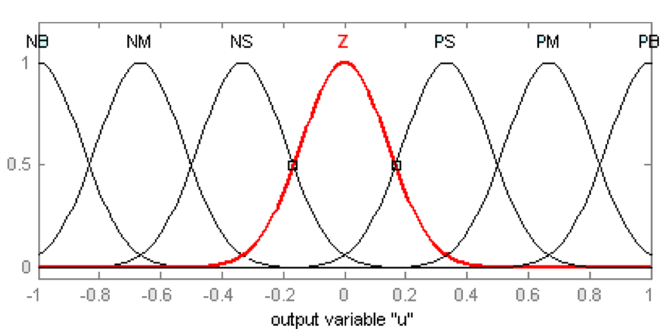

Fig. 6. Membership functions for the output variable 'u'.

Table 1
Two dimensional fuzzy rules to compute u.

z_e	w						
	NB	NM	NS	ZE	PS	PM	PB
PB	Z	PS	PM	PB	PB	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PS	NM	NS	Z	PS	PM	PB	PB
ZE	NB	NM	NS	Z	PS	PM	PB
NS	NB	NB	NM	NS	Z	PS	PM
NM	NB	NB	NB	NM	NS	Z	PS
NB	NB	NB	NB	NB	NM	NS	Z

minus the measured depth. After carrying out the stability check using different kinds of membership functions, Gaussian membership functions are finally used for representing the input and output variables as shown in Figs. 5–6. Using a trial and error approach, the best inference mechanism to use in this case seems to be the prod-probor method. Because of simplicity and availability of the graphical user interface (GUI) in MATLAB, the Mamdani inference engine (Palm et al., 1997) is employed for designing the FLC that uses the minimum operator for a fuzzy implication and max-min operator for composition. The defuzzification technique used is found using a trial and error and centroid method is the one which provides least integral square error. Table 1 shows fuzzy rule base consists of 49 rules for computing the output variable, which are formulated based on the author's experience in performing numerical simulation using depth error and depth rate as the system states and change in volume of gas inside the lift bag as the output. The definition of fuzzy control actions are defined in Table 2.

The variation of control action 'u' with respect to the depth error (z_e) and depth rate (w) is shown in Fig. 7. Positive value of u implies filling gas inside the lift bags, where as negative value implies taking gas or purging gas out from the bags. Thus by the combined action of filling gas in to the lift bag and by regulating the purging of gas through the valves in accordance with the depth error and its derivative, a stable ascent can be ensured.

4. Numerical results and discussion

The performance of the supervisory fuzzy logic controller is investigated by conducting numerical simulations on a small-scale pontoon model in MATLAB & SIMULINK. The pontoon is a rectangular-shaped structure with watertight compartments for internal deployment of lift bags and gas generating system. External lift bags are also provided for achieving the desired lift. Normally internal bags are placed inside the vessel to make sure that centre of buoyancy C_B is above the centre of gravity C_g for stability. The lift bag diameter and length are 1.129 m & 1.8 m respectively and the maximum space inside a single compartment for the installation of a gas generator including piping is 0.29 m in diameter and 2 m in length (SuSy, 2011). Fig. 8 exemplifies the installation of inflating system inside a single pontoon compartment. The weight, length, breadth and mass moment of inertia about Y_b axis of the pontoon model are 9320 kg, 6 m, 3 m and 1481.31 kgm^2 respectively. The hydrodynamic coefficients used in the simulation are $Z'_{\dot{w}} = -0.0157$, $Z'_{\dot{q}} = -0.00041$, $Z'_{w} = -0.043938$, $Z'_{q} = -0.017455$, $M'_{\dot{w}} = -0.00053$, $M'_{\dot{q}} = -0.00079$, $M'_{w} = -0.011175$ and $M'_{q} = -0.01131$ respectively (Fossen, 1994, 2002; Ridley et al., 2003).

Simulation is performed for the pontoon model, which is laying at sea bottom having distance of 250 m, 300 m & 350 m from the sea surface and the obtained responses are plotted in Figs. 9–13. According to Section 2.1.1.3, the lift force required for the pontoon model can be estimated as 103341.68 N (of the order of 10^5). According to Foda (1982), for the estimated break out force, the break out time can be obtained as 100 s. The buoyancy force provided by all lift bags are considered as a whole in the rigid body modeling approach.

Table 2
Definition of fuzzy output control action.

Output '*u*'	Meaning	Control Action
Z	Zero	Both Primary and Secondary controllers are off
PS	Positive Small	Small rate of filling gas in to the lift bag: operating primary controller
PM	Positive Medium	Medium rate of filling gas in to the lift bag: operating primary controller
PB	Positive Big	Large rate of filling gas in to the lift bag: operating primary controller
NS	Negative Small	Small purging of gas from lift bag: operating secondary controller
NM	Negative Medium	Medium purging of gas from lift bag: operating secondary controller
NB	Negative Big	Large rate of purging gas from lift bag: operating secondary controller.

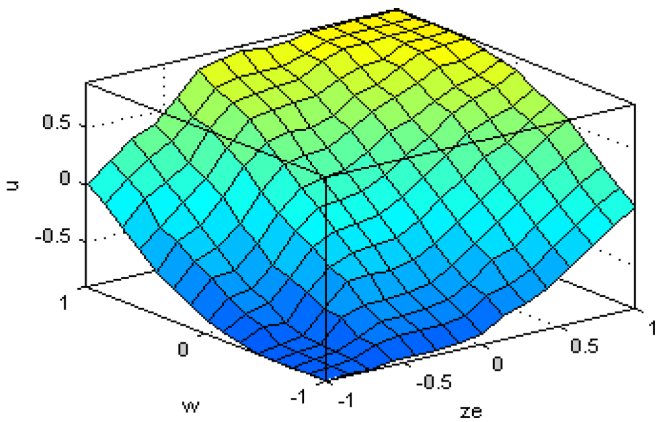

Fig. 7. Variation of control action with depth error and depth rate.

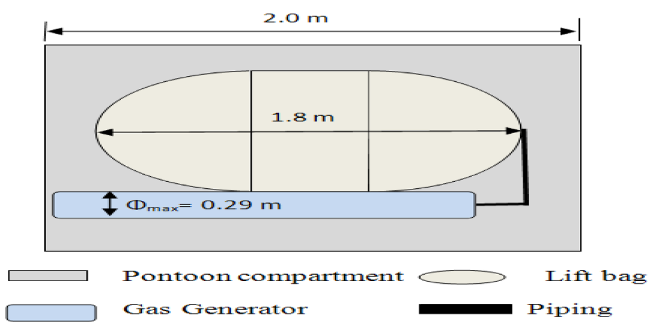

Fig. 8. Pontoon compartment with inflating system (SuSy, 2011).

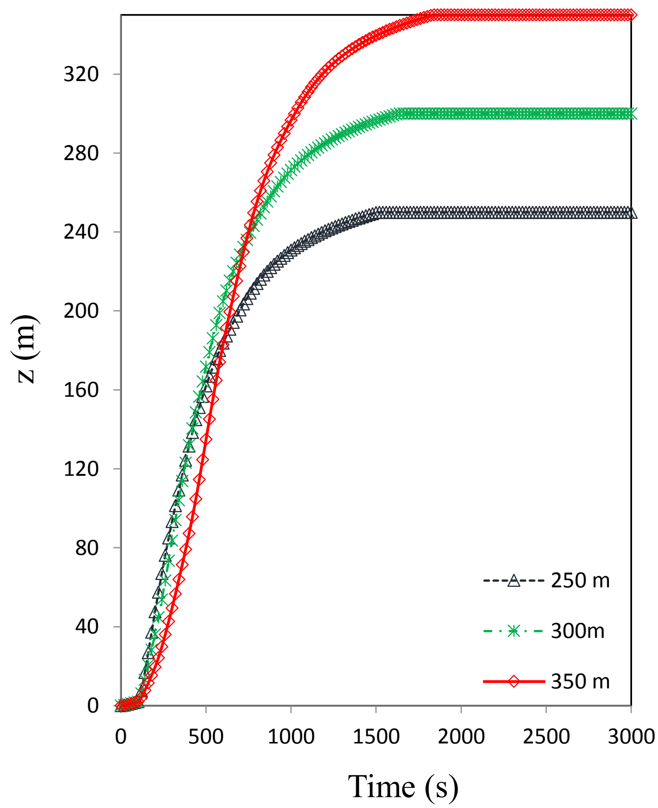

Fig. 9. Variation of ship vertical position from sea bottom.

Fig. 9 shows that in all the three cases the pontoon reaches the target depth in 1600s with no overshoot and less steady state error. It is seen that after reaching the target depth, even if the simulation time is increased, it has no effect on the system performance. The maximum value of ascent velocity among the three target depths is found from Fig. 10 to be 0.45 m/s (< 0.6 m/s), which leads to the conclusion that the controller is capable to maintain ascent velocity within the stable range (JW Automarine, 2010) for even higher water depths. From Fig. 11, the maximum value of pitch angle for the three cases is found to be 13^0, which shows that pitch is stable (< 15^0) (Beyazay, 1999). Pitch rates for the three cases approaches zero when the pontoon reaches the commanded depth as shown in Fig. 12. Fig. 13 shows how the fuzzy control action regulates the volume inside the lift bags according to the depth error and depth rate for a stable ascent. It is noted that the controller initially sets positive flow rate for suction breakout and after the suction breakout (i.e.100 s), the controller reduce the flow rates to negative value in order to overcome the excess buoyancy available and thereafter maintains a constant value for handling the variation in additional buoyancy due to the expansion of gas inside the lift bags with respect to the decrease in depth and finally reaches zero value after the pontoon reaches the commanded depth. From the simulation studies it is found that the proposed supervisory FLC is suitable for maintaining hydrodynamic stability for even higher commanded depths by suitably designing the fuzzy membership functions, scaling factors and linguistic fuzzy rules.

5. Conclusions

A rigid body mathematical formulation for the dynamics of raising sunken vessel using buoyant systems is derived according to the principles of underwater dynamics, thermodynamics and soil-structure interaction problems and a state space model is developed from the equation of motion in diving plane for integrating the controller. In the rigid body modeling approach, additional buoyancy provided by all lift bags are considered together and the overall system behavior is analyzed. Purge valve modeling is carried out according to Farrell (2008). In order to ensure hydrodynamic and structural stability during a salvage operation using buoyant systems, two control subsystems are

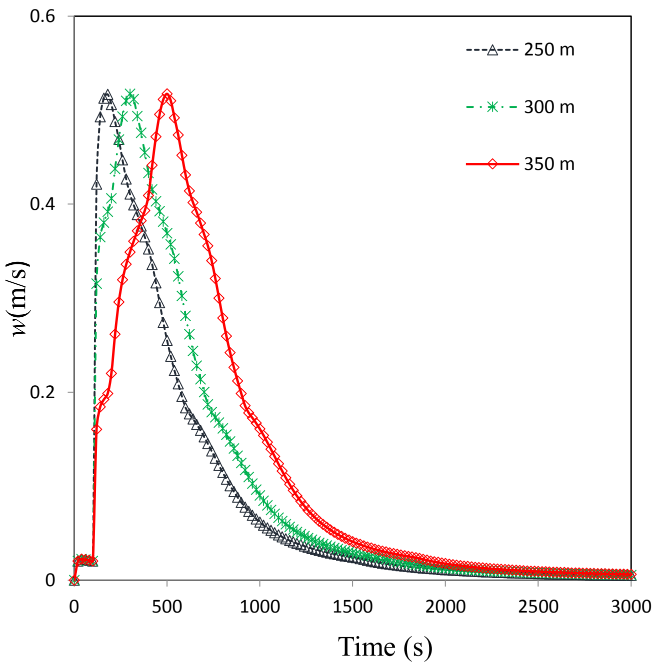

Fig. 10. Variation of ship ascent velocity.

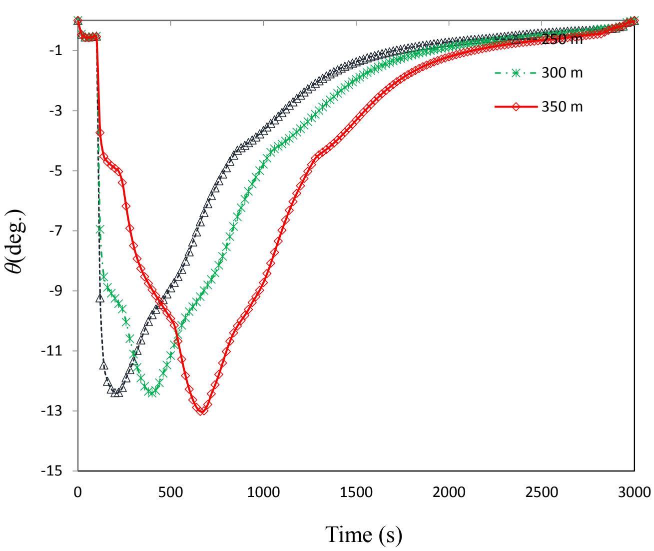

Fig. 11. Variation of ship pitch angle.

proposed; a sliding mode controller as the primary controller for regulating the inflow of gas in to the lift bags and a PID controller as the secondary controller to regulate the purging of gas through the lift bags. Then a supervisory fuzzy logic controller is suggested to monitor the primary and secondary controllers. Simulation studies reveal the fact that for complicated non linear underwater operations, like marine salvage, involving uncertainty and external disturbances a closed loop control system is mandatory and supervisory FLC is capable to maintain hydrodynamic stability in the diving plane for even higher water depths without overshoot and less steady state error. This is because the FLC uses a non linear control law that is developed based on the author's experience in conducting numerical simulations on primary and secondary controllers and also due to the stability analysis by using different combinations of fuzzy membership functions and scaling factors by the trial and error method. Thus the supervisory fuzzy logic controller becomes adaptable for a safe and viable salvage operation.

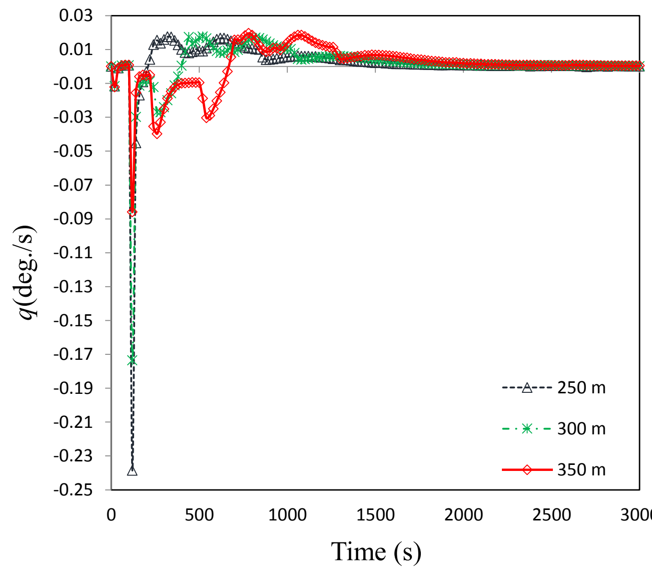

Fig. 12. Variation of ship pitch rate.

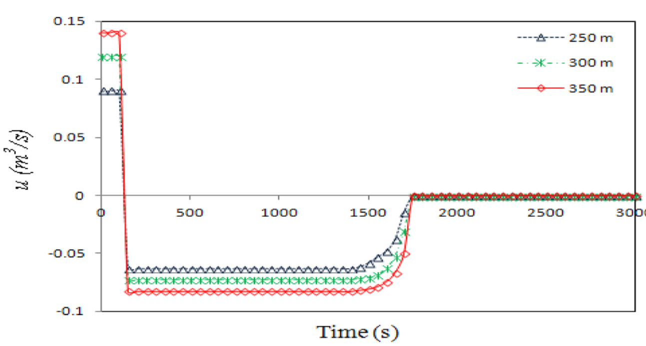

Fig. 13. Net flow rate (at local pressure) in and out of lift bags.

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