# A Novel Underwater Micro AUV for Submerged Surface Inspection Using Hydrodynamic Ground Effects

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This introduction acts as an abstract - it generally motivates the research with a real problem that could be solved with one approach if some of the basic physics were better understood.

## INTRODUCTION

Motivation

Current barriers + research goals

Anticipated growth of sub-sea technologies for security, infrastructure inspection, and exploration, motivates a deeper understanding of underwater navigation in proximity to a submerged target surface. Common examples ranges from water tanks in nuclear reactors and other DOE facilities to submerged oil rig infrastructure, ship hulls or hidden threats. We propose the use of a water jet propelled ellipsoidal micro autonomous underwater vehicle (AUV) called EVIE (Ellipsoidal Vehicle for Inspection and Exploration) with a flattened base to house necessary sensors needed for surface inspections.The AUV is designed - both in terms of it's shape and jet nozzles - to be appropiate not only for freestream motion for doing visual inspections but also to allow it glide on submerged surfaces to inspect hidden internal damages. One of the main challenges of moving on submerged surfaces without wheels or tether is that the surface roughness can impede the motion. Our research goal is to explore the ground effect hydrodynamics due to the relative motion of the robot which can allow the formation of a small fluid bed layer between the bottom of the body and the surface- thereby enabling smooth motion. Use of ground effect fluid dynamics - is common in both aerial and land vehicles but almost unexplored for underwater environment. Preliminary results of experiments carried out look promising and novel for consideration of more extensive research. The natual hydrodynamic ground effect force cause a self stablizing phenomenon-which keeps the AUV at a fixed height- in order of few millimeters - from the surface- applying attraction if it goes away from it's stable point, and repulsion if it pushes down hard on the surface. The force is very non linear in nature- and yet for practical application a system model ideal for feedback control must be developed. The PhD research therefore proposes investigation of a less explored but highly interesting concept- i.e. utilization of hydrodynamic ground effects for design and control of a micro AUV for submerged surface inspections. This work would involve hardware design and integration, computational fluid dynamics (CFD) simulations, experimental validations, and mathematical modeling for system dynamics and control.

Background establishes the value of the proposed solution, if it works

## SYSTEM DESCRIPTION: THE ROBOT EVIE

A great deal of research is being done in underwater robotics to develop sophisticated systems for inspection and maintenance of underwater structures . One common method is visual inspection; but it cannot locate subsurface features such as internal hairline cracks in weld seams of boilers in power plants or other DOE water facilities and tanks [1] [2]. Ship hulls inspection is another task which requires more than just visual inspection [3]. For port security, it is important to monitor small ships and boats carrying contrabands including in hidden cavities in the ship bottoms [4] or perhaps even unidentified objects disposed in the near coast regions. A quick yet thorough subsurface test of the targets is necessary in such cases. Prevalent methods for subsurface testing of metal structures are ultrasonic testing (UT) [5] and eddy current testing (EDT) [6]. UT is commonly used by placing the sensor in direct contact with the target surface. However, on-contact surface scanning can be slow if the surface isnot smooth. Further in many applications such as in ocean security contact with foreign submerged targets might be undesirable or unsafe. A prototype robot, EVIE (Ellipsoidal Vehicle for Inspection and Exploration) [7], shown in Figure 1 was tested first with surface contact.EVIE is an ellipsoidal robot, 203mm152mm an aspect ratio of 4:3,optimal for the system to be highly controllable [8]. Size can be adjusted to accommodate electronics and the sensors, though smaller size provides better maneuverability. The robot can have upto 6 jets - which allows 5DOF motion. However for our research, we intend to limit the work to motion on a horizontal surface and in calm or non turbulent water.

It was found that motion with full contact with underwater surfaces, including those with minimal roughness can decrease velocity by over 30% when compared to that in free stream; while tacky material (Vaseline) results in a significant speed fluctuation. Therefore, non-contact inspection is desirable- by allowing a thin fluid film between the surface and the robot's bottom. It would provide faster and more reliable inspection without being disturbed by the surface roughness and its varying

Background section intersperses motivation and state-of-the-art with problems in the field, and justifications for design decisions in the proposed solution

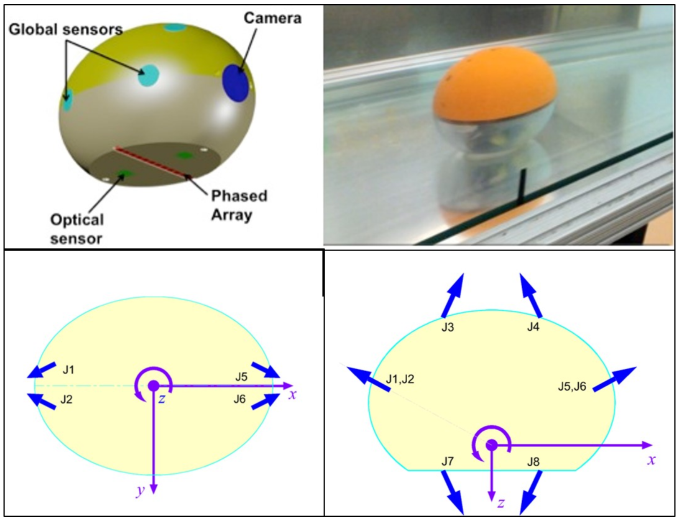

Fig. 1: (a)Top Left: Conceptual micro AUV for submerged pipe inspection (b) Top Right: Actual Prototype moving on a surface in a 3ft deep tank using water jets for propulsion(c) Bottom Left: Top View of the Jet Locations(d) Bottom Right: Side View of the Jet Locations

properties. Both for ocean security and maintenance of other submerged structures, high speed non contact inspection can prove to be an invaluable technology.

Presently there are different robots for underwater structure inspection or maintainance. Most are tethered which can lead to snagging in a cluttered environment. Other robots involved in ship hull inspection or maintenance are usually crawlers or wheeled and uses magnets to ensure contacts [14]. These robots are generally large and propelled by powerful actuators. The proposed ground-effect approach will provide an effective alternative to those existing robots. It is expected that we can build a compact, untethered robot that can maneuver across rough surfaces and scan them with higher speed.

In order to address this goal, we make use of the fact that subsurface inspection using UT can also be performed with the sensor placed at an odd multiple of quarter wavelength where the reflected waves from the surface adds in phase at the transducer[12]. Figure 2 illustrates the resonance for a non-contact sensor. For a 300KHz UT transducer having wavelength 4mm in water $(cw = 1500m = s)$, the transducer needs to stay at 1nmm from the surface, where n is an odd number. Shifting the sensor from quarter to half wavelength cancels the pressure building up process, leading to weak subsurface transmission (figure 2b).

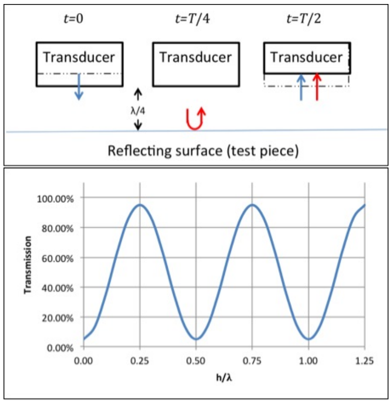

Fig. 2: Top: Schematic illustration coherent wave behavior at quarter wave gap. Bottom: Transmission efficiency vs distance assuming 90% reflection (10% transmission) at the test surface, and 100% re-absorption at the transducer when placed at quarter wavelength distance

The above phenomenon motivated us to explore a novel method of robotic subsurface inspection where the robot scans the surface by maintaining a controlled gap. A simple method is to form a tight feedback control to regulate the gap. In an underwater environment, however, such a brute force control method requires powerful and extremely fast responding actuators, which might not be even feasible. Therefore our research proposes to explore alternative approaches that uses both natural and

Much of the background has built up to this one problem at the core of the thesis - the control architecture necessary to make this acoustic technique feasible

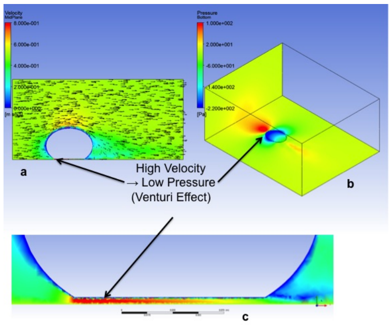

Fig. 3: (a)Velocity(left) and (b) Pressure (right) distribution between the bottom of EVIE and the surface for u=0.5m/sec and h=5mm

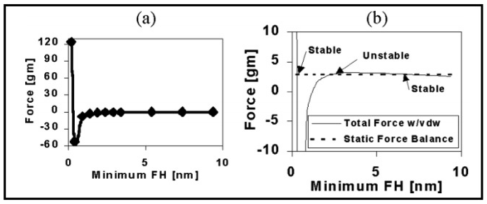

Fig. 4: Stability curve: Fz versus gap for a HDD slider

induced hydrodynamic effects between the vehicle bottom surface and the external target surface. Namely, we exploit the so called ground effect  the change in fluid behavior near a surface, to create a self stabilization mechanism.

now, the technical background and initial results validate the specific approach for the thesis

## UND EFFECT FORCE

Ground effect is the change of fluid field around the body due to the presence of an external surface, whether or not that surface is the ground. A more general name would perhaps be "surface effects".However, in context of this research, we are exploiting the effect much similar to how aerial or land vehicles exploits the ground for motions- therefore the name. Computational Fluid Dynanimcs (CFD) simulations of the robot moving at different heights from a submerged surface first revealed the effect of the ground on the moving body. This is shown in the figure 3. It shows the body experiences repulsion from the surface at extremely small gaps, suction at somewhat larger gaps (one or more body lengths)

Some well known applications using the fluid flow effects in the vicinity of the ground, and their relation to our work, are worth mentioning here. Fluid forces on the body due to the presence of ground depends on the characteristic gap ratio, $\epsilon = h/c$, where h is the distance of the surface from the ground and c is the chord length of the body. A Formula 1 race car uses the fact that at $\epsilon \approx 0 : 1$the body experiences a suction (Venturi) force which enables greater acceleration. However, for $epsilon \leq 0 : 08$ it was found that boundary layers merge and instead a lift force occurs [9] [10]. For self stabilization, instead of a constant down (car) or up force as in Wing in Ground Effect Vehicles, our goal is to attain a zero force region with a steep gradient. A more relevant example was found to be the air bearing slider mechanism for hard disk drive (HDD) [11]. Figure 4 (credit B. Thornton and DavidB Bogy) shows a graph of how the Z force varies in a slider as the gap h is changed [12]. The graph shows the slider has a stable region at 2nm, where $Fz = 0$. Greater than 2nm, the slider experiences a suction force to bring it back to the stable point. When h is less than 2nm, slider experiences a lift force to push it up to the stable point. HDD calculations are complicated by the distance scale. At the ¡10nm fly height of a modern HDD, the gap is comparable to the mean free path of molecules in air. Navier- Stokes must be modified to incorporate intermolecular terms. We propose to explore the possibility of imitating the qualitative behavior of HDD slider in a macro scale in anunderwater environment for self stabilization of autonomous robots for surface inspection. Our priliminery results looks promising enough to continue in this direction.

Depending on the shape, geometry and most importantly the characteristic gap ratio $\epsilon = h/c$, a body moving near the vicinity of an external surface experiences lift, suction or can even be self stabilized. For simplicity, we can define three regions in the flow field near the surface underwater:

- a) Region extremely close to the surface with high viscosity. Flow in this region is most effectively understood through the interaction of the boundary layers [17]

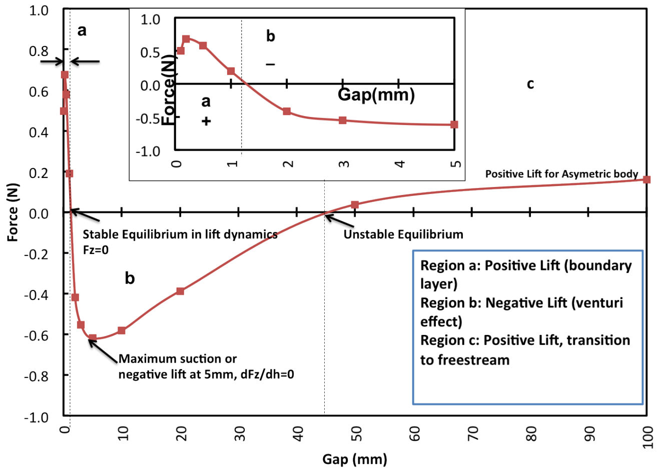

Fig. 5: Shows the three regimes: (a)$h/c \leq 0:01$ (b) $0:01 \leq h/c \leq 0:3$ (c)$0:01 \leq h/c \leq 0:3$ and how $F_g$ acts in each for EVIE moving at 0.5m/sec

- b) Region close to the surface but outside the region of boundary layer interaction. In this case, there is a flow channel between the body and the surface. Increased velocity in this channel leads to low pressure (suction) which is called the Venturi Effect.
- c) Region further from the surface where the effect of the ground becomes less pronounced and the the flow transitions into the unbounded medium.

The force curve characteristics from CFD simulations shown in Figure 5 look very similar to Figure 4 of the HDD force curve. Extremely close to the surface, below 2mm (region a) there is a lift force on the body. The body stabilizes at 2mm, where all the forces balance. Above 2mm (region b) the Venturi force pulls the robot towards the ground. There is a second equilibrium point around 50mm, however this is unstable (positive slope). Above 50mm there is again a net lift force which extends out to large distances as the body smoothly transition to free stream behavior.

The research goal here is to understand this ground effect force- how it is affected by the system design, shape, scale and other parameters as well as validate through experiments the occurence of the phenomenon (in water tanks or tow tanks). The natural hydrodynamic effect we noticed might not be be fully appropiate in a practical application- since CFD simulations use ideal environment. It will be interesting to explore possibilities of jet induced ground effect hydrodynamics for forming a fluid bed and learn from concepts ranging from a fluid bearing to vertical take off and landing vehicles [15]. The concept is shown in the Figure 6 below.

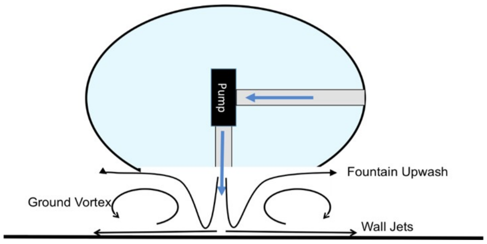

Fig. 6: Use of jet induced hydrodynamics for fluid bed formation and height control

## THE SYSTEM MODEL

Hydrodynamic force on a body in motion in the vicinity of a submerged surface is substantially different from motion in the free stream and is under-explored. The $F_g(h)$ curve is unique and challenging to model - particularly due to the presence of multiple equilibria- one stable at very small distance and one unstable at a comparatively larger distance. The system dynamics is characterized by complex non linearities which are non monotonic in nature. Traditional linearization techniques though most preferable cannot capture the behavior of the body in the entire near surface region of operation (about 1m for a body of comparable size to our robot), which limits on how we can model a linear controller for the same. We have already demonstrated closed loop feedback control for overcoming munk moment and maintaining heading angle on a surface at the research presented during the qualifying exam. Model linearization on the plane without accounting for the non linear ground effect force was straight forward. The more challenging part is the height control in the presence of $F_g$. In this case we may assume a single bottom jet for height control. The complex non linearities though command non linear modeling and control- it is interesting to explore data driven linearization via studying system performance and investigate possibility of using linear control by capturing the non linearities in what we call a “pseudo linear model” which follows the same structure as $\dot{x} = Ax + Bu$ This part of the research aims to focus on system dynamics and modeling using a novel data driven approach. The background for this is explained as below.

The non linear model of the single axis vertical motion of the jet impinging robot can be given as

$$\dot{w} = \frac{1}{S_z}[(mg - F_b) + F_g(u, h) + F_D + F_j] \tag{1}$$

$$\dot{h} = w \tag{2}$$

where, $F_d$, the drag force (if considered quadratic) is given by $Fd = Z_{ww}w^2$, and $w$ is the vertical velocity of the robot or plate. The non linear terms - $F_g$ and $F_D$ - are major constrains to linearize the above equations for constructing typical state space equations. For traditional linearization, we consider only the area of interest - up to the upper bound of the venturi or “suckdown” region. The simulation data is fitted into a quadratic functionas which is then linearized.

$$\dot{w} = \frac{1}{S_z}[(mg - F_b) + u_j[\alpha h^2 + \beta * h + \gamma] + Z_{ww}w|w| + u_j] \tag{3}$$

$$\dot{h} = w \tag{4}$$

Here $u_j$ is the thrust control which regulates the thrust force of the bottom jet $F_j$ and goes quadratic as voltage $V$ or jet velocity $w_j$. In the region of the operation, the drag function is complex as well. It is linear in very small gaps and slowly transitions to quadratic in larger gaps. For a fixed thrust force, the ground effect could be assumed to depend only on height, i.e. $F_g(h)$

Let us now consider the equilibrium position, for a constant $u_j = k$, as the position of the stable height where $F_g = 0$, and remap it to h=0 by shifting the $F_g$ curve to pass through (0,0). Here the parametric model is now linearized at the equilibrium- that is - are $w_e = 0v/sec$, $h = 0m$. When the values are substituted in the Jacobian matrix of the state space model, the damping term disappears leading to the failure of the linear model.

After the necessary technical background, the very specific contribution/approach is proposed

This is a simple way to show traditional state space model cannot capture this highly non linear system characterisitcs.

Given, there is no simple linear model to capture the non linearities, we propose to explore the idea of using data, i.e. experimental or CFD simulation data of the system for coming up with a unique linear model that is capable of capturing nonlinearities. This can be done by augmenting ”auxiliary variables” i.e. $F_g$ and $F_d$ associated with the non linearities as additional state vectors. We intend to explore relatively new methods of system identification, namely “subspace method” or 4SIDmethods (Subspace State Space Systems IDentification) as well as Principle Component Analysis for developing the linear model. Let $\tilde{x}$ represent the augmented state vector which is given as below. We feed the algorithm with the known information- that is, the height, the velocity, the ground force and the drag force from experiments (or simulation data). The input is the external input to excite the system over the region of operation. We intend to use this response as our training data. The augmented state variables are given by:

$$\tilde{x} = \begin{bmatrix} h \\ w \\ Fg \\ Fd \end{bmatrix} \tag{6}$$

Our goal is to use this new approach of augmented state vectors in a higher dimensional linearized model to capture non linearities in the system state matrix $A$ and apply linear feedback control on the system. We want to exploit the fact that nonlinear dynamical systems behaves linearly when it is recast in a high-dimensional latent variable space as in research explained [19] [20]. Finally for appropiate control, we must know the anticipated ground effect force. We intend to develop a model that can help us to estimate the same which can be therefore utilized in our feedback loop.

Conclusions re-establish the thesis objectives and proposed work.

## CONCLUSION

Our first part of the research will be focussed on exploring and understanding this new hydrodynamics phenomena in connection to the robot or AUV. The second part we would focus on validations of the concept via simulations and experiments. Finally, we expect to work on a novel method of modeling the system in non linear ground effect- a research area severely underexplored. We intend to work on a method of establishing a data driven linear state space model. Such a data driven method is highly impactful for complex non linear dynamical model whose system information is prior unknown, and perfect system modeling is not possible.

The proposed PhD research therefore aims to cover three important aspects to enable a complete design and modeling analysis of the proposed novel micro auv for submerged infrrastructure inspection. These are - a) design and development of the micro-Auv b) understanding and characterizing the ground effect hydrodynamics related to the motion via simulation and experiment c) developing the system dynamics model for the original non linear system through an unique data driven method.

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