Applications and Prototype for System of Systems Swarm Robotics

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***Abstract*— In order to develop a robotic system of systems the robotic platforms must be designed and built. For this to happen, the type of application involved should be clear. Swarm robots need to be self contained and powered. They must also be self governing. Here the authors examine various applications and a prototype robot that may be useful in these scenarios.**

Keywords*— *Robots, Underwater vehicles

I. Applications Opportunities for Swarm Robotic System of Systems

A. Steps towards realization

Adapted from Farinelli et al. [1]

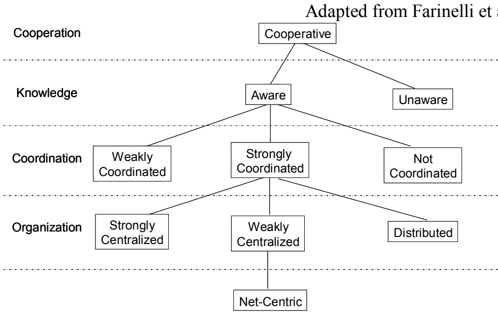

Figure 1 A taxonomy for swarm robotics

The first step towards realization of a robotic swarm is to develop actual robots in the lab on a small scale to discover physical characteristics and technologies that cannot be so easily simulated. This is already well underway at the University of Texas, San Antonio (UTSA) Autonomous Control Engineering (ACE) laboratory with land and sea based robots, with some initial work on air based robots. Small swarms of robots are being investigated with real equipment, while scalability will be tested with simulations based on the knowledge gained working with real robots.

After proof-of-concept is sufficiently accomplished with small swarms of real robots, simulation can be used to test scalability to many robots working together as a net-centric System of Systems. Economically it is not feasible to experiment with such large scale System of Systems in early stages of research. There is also some risk of actual robots experiencing damage during testing in a real environment, which is avoided when doing simulations. Simulation can provide a safe environment where correct programming can be verified before implementing some algorithms directly on robot. Coordination of autonomous robots is difficult and might otherwise be too risky for a robot swarm can be tested with simulation. This avoids scenarios where a fault in programming would cause collisions damaging robots or their environment. Some tuning can be decided during simulation so as to reduce the likelihood of collision. A simulation can provide results that are not easily experimentally measurable with currently available technology. The testing of robots for long periods of time can cause wearing of robots which can be prevented using simulations. There are some drawbacks to relying on simulations as well. For example, the result of simulations may not be always accurate as expected in real time. This calls for both simulation and development of physical robotics in an integrated plan.

Simulation is to be carried out to demonstrate the use of robotics in a net-centric System of Systems to profit mankind. We considered many applications, taking into account negative consequences as well as benefits. For example, sending robots to dig through rubble after a major disaster in search for survivors could cause undue harm to people who are trapped in the rubble if the robots are less able to adapt to people's cries for help or verbal cues from the disaster victims. Alternatively, overly-centralized fully-automated military or police forces were considered, and the likelihood that they might be hijacked and used for harm or tyranny would also be a regrettable.

Adapted from Jacoff et al., (2000)

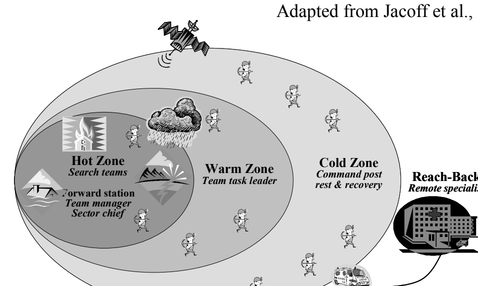

Figure 2 Urban Search and Rescue

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B. Urban Search and Rescue

One possible application of robotic swarms is their proposed use in Urban Search and Rescue (USAR). Jacoff et al. defines USAR as follows: “USAR is concerned with rescue activities in collapsed building or man-made structures after catastrophic events, such as an earthquake or bombing” [2]. Murphy et al., suggest the following scenario. Make use of land, aerial and/or aquatic robots cooperating together to search for and rescue people in dangerous environments. This scenario is shown in Figure 2. When a disaster occurs, Unmanned Air Vehicles (UAVs) inspect the area under consideration and send collected data to the command center. Then the command center divides the disaster affected area into three zones: hot zone, warm zone and cold zone. The hot zone is the area where the disaster actually occurred. The warm zone is the nearby area where robots can rendezvous. Warm zone can be defined as the area where there is the possibility of human rescue teams to act without a high risk of danger. The cold zone is the surrounding area for repairing and recharging robots. The cold zone has the lowest possibility of danger. In this zone, rescue teams can put together control units to control the robots in hot zone and cold zones. After an initial aerial survey, land robots enter the dangerous area out of safe reach of human rescue teams. Once survivors are found, they are recovered by the robots to a safe area and then transported to a nearby hospital [3].

Use of robotic swarms for search and rescue must be carefully thought out so that the robots do not become a distraction to emergency workers or unintentionally injure people in distress by being less perceptive and adaptive than human rescue workers. For this reason, use of robotic swarms is potentially most helpful for covering large areas in searching prior to the use of human rescuers with more limited robotic assistance for more sensitive tasks in areas where human rescue teams can safely work.

Courtesy Bureau of Industry and Security, U.S. Department of Commerce

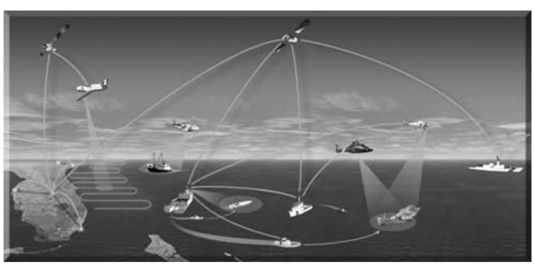

Figure 3 Coast Guard Deep Water Program

The Coast Guard patrols the coast and maintains navigational markers such as buoys and lighthouses, performs search and rescue operations, and patrols the waterways and coastal borders. An important part of the coast guard program is to communicate and co-ordinate with each other and work together. The Coast Guard Deep Water Program, illustrated in Figure 3, is an existing System of Systems that operates in air, sea, and land.

This System of Systems has many tasks that could potentially benefit from the use of swarm robotics. In fact, robotic drone aircraft are already being introduced. Robots can cover large areas efficiently, and to go where it is unsafe for human activity, or where it is impractical to achieve the desired level of patrolling

C. Area Surveillance

A problem of interest is the formation of a group of UAVs that fly together to carry out assigned missions along with land and water robots; Having defined the desired surveillance area, control laws are designed to achieve formations according to one of the following scenarios: 1) Each UAV takes off toward its corresponding surveillance area and locks onto it in finite time; 2) UAVs take off independently of each other and one at a time; 3) All UAVs take off simultaneously towards their corresponding surveillance area and lock onto them at the same instance of time. Examples are presented to illustrate the efficiency of the designed GPS waypoint navigation. One scenario to form such a group is as follows. Have one master unmanned aerial vehicle equipped with sensors, cameras, and a communication system. The master UAV can then determine a safe and surveillance area for itself and other UAVs. It can then communicate with the other UAVs and let them know the areas they should monitor. The follower UAVs should be able to fly towards their corresponding surveillance areas put forward by the leader quickly and locks onto them (ideally in finite time). When all UAVs are locked onto their area and fly together, resembling a flock of birds flying.

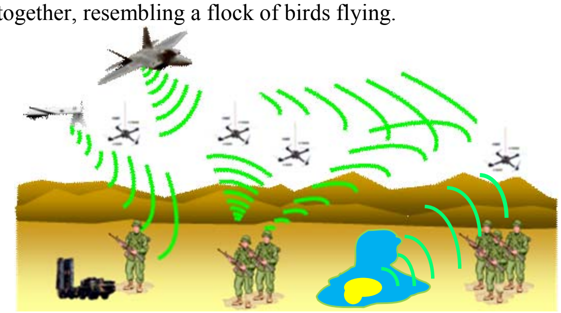

Figure 4 Illustration of UAV’s working in a military scenario

D. Harvesting Natural Resources

Manganese nodules are naturally occurring mineral deposits on the ocean floor [4], [5]. They are typically several inches in diameter, and they contain metals that could be harvested commercially. Mining of these metals by divers is not practical because of the depth at which they are located and the dangers and expense associated with such dives. However, Autonomous Underwater Vehicles (AUVs) could be sent in swarms to the seabed to search for and harvest nodules, as shown in Figure 5. As the nodules from the seabed are recovered, they would surface, where they could contact other vehicles such as Unmanned Air Vehicles (UAVs) to pick up the goods and to provide fuel for the submarines. The UAVs could pick up the nodules and deliver them to land-based operations, such as awaiting Unmanned Land Vehicles (ULVs) which would be able to deliver them to processing facilities that might be collocated to energy sources several miles inland. Geothermal energy is available on the slopes of active volcanoes such as Mauna Loa on the island of Hawaii. Energy could be harnessed to provide not only electricity and mechanical power, but it could also transform abundant rainwater into hydrogen fuel. This scenario combines the use of swarms of robots in land, air, and sea to benefit mankind while minimizing dangers. Feasibility would depend upon many factors, including potential political implications in dealing with emerging groups like the International Seabed Authority. Regardless, this System of Systems application was selected as the primary long-term goal of our initial swarm robotics simulation effort.

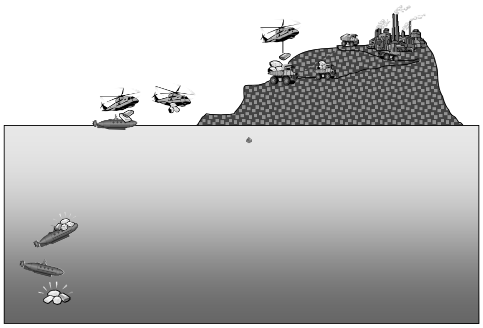

Figure 5 Harvesting manganese nodules

II. A PROTOTYPE

To be able to perform in the applications described the underwater robot required needs a good amount of flexibility of motion. The robot described herein uses the minimum number of thrusters required to control the robot without requiring any momentum for steerage. It has three vertical thrusters, 2 forward and 1 aft, for depth and dynamic levelling and two horizontal thrusters for motion control.

Apart from the chassis of this prototype, most systems described are used in the land and air based robot prototypes.

III. CHASSIS

A. Body

The main body consists of 500mm of 90mm diameter DWV PVC pipe. DWV (drain, waste and vent) pipe has a larger wall thickness and will make the robot stronger and able to withstand the pressure at greater depths. On each end of the pipe is glued a grate collar. This will be capped with a clear disc and a 3 mm thick o ring. The disc can be attached on with stainless steel screws outside the o ring.(Figure 6)

The eight screws are place outside of the o ring so that they do not interfere with the watertight seal. Removing them gives easy access to the body from both ends. The grate's wall thickness is thick enough so that it may be tapped to receive the screws. If it is not thick enough nuts can be placed behind the grate collar.

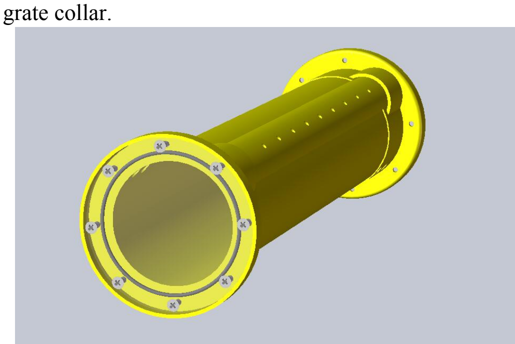

Figure 6 Robot body with sealed ends and Ballast strip

The capping disc, apart from creating a view port for a camera, also allows visual inspection of the o ring to ensure a watertight seal. A one quarter section of the 90mm pipe can be used as a base to slide the electronics into the body.

B. Ballast and Floatation

To give to robot some balance and to trim the weight a ballast system is required. A one third section of 90mm pipe with a series of tapped holes affixed to the bottom of the body can be used to attach small weights. (Figure 6)

Depending on the weight of the electronics bay, a robot of the size describe above may require some more floatation. Two 40mm diameter pipes along each side of the top of the body will add enough floatation. (Figure 7)

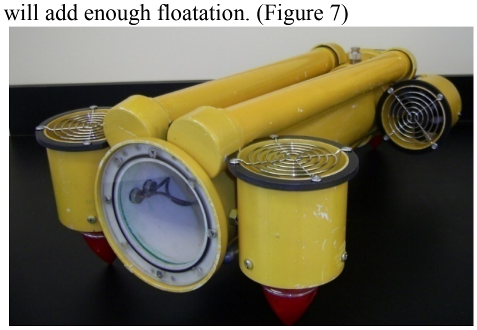

Figure 7 Robot chassis and thrusters with floatation units

IV. PROPULSION UNITS

A. Thrusters

The initial prototype used bilge pump motors for the thrusters as seen in Figure 7. These were only good for shallow water. A better thruster was required.

Thrusters can be very expensive units. Motor shafts, being a moving part, are hard to waterproof. The following design enables all the electronics to be encapsulated in plastic, removing the need for a shaft seal.

The thrusters described herein are meant for the autonomous underwater vehicle targeted more than 1 m. Figure 8 shows the basic design of the thrusters

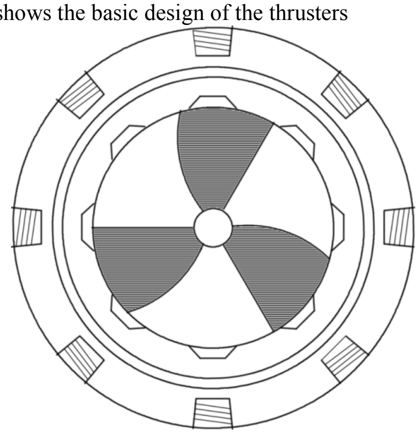

Figure 8 Conceptual design of the thruster unit

The central part is the propeller, and the blades of the propeller are protected by the fair thin duct of thickness around 50mm around it. The thrusters are tend be electric using brushless DC motor (BLDC). BLDC is used for it is more efficient and reliable. BLDC have linear speed Vs torque characteristics. A BLDC has a wound stator, a permanent magnet rotor assembly, internal or external devices to sense rotor position. BLDC motors have many advantages over brushed DC motors and induction motors. A few of these are:

- Better speed versus torque characteristics
- High dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges

In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors. BLDC is synchronous 3-phase type of motor with the power available of 186 W. The motor is for six poles. The motor rotates from 15-7.5 mechanical degrees per step and the six pole motor rotates using 2 circuits at 15 degrees. Rotor forms a ring around the propeller and the stator is encapsulated in the thin duct that surrounds it. The stator can be placed inside or outside the rotor, here it is placed outside. The rotor and stator fit within the volume of the thin duct. The magnetic field intensity of the magnets of thickness 1.5mm is 11,400 H. The load on the motor is expected to be 18 Kg. The motor is controlled using H-bridge on PIC microcontroller board. Two H-bridges, with a maximum frequency of 20 KHz, are used for the control of the motor where each of them can control single phase and multiple phase of that pole. Each one has to control 3 pole sets with 2742.9 poles send to a second. The submarine is expected to sustain in water for 2 hours on a 24V 9Ah supply with all the above mentioned assumptions. The basic required calculations are:

Back EMF = -p*max flux*sin(rotor position* φ)* (D φ / Dt)
Where,
p is the pole pair
D is the diameter of the stator

Torque Tind =(AG/ μ)*Bloop *Bstator*sin theta
Where,
G is the geometry of the coil
A is the area of the coil
μ is the permeability of the stator material

Npulses = NPnm
Here N is the number of phases.

Force between two poles, F = μ*q1m*q2m/ (4*pi*r^2)
Where,
qm1 and qm2 are the pole strengths (SI units: Newton)
r is the separation (SI units: meter)

V. Control System

A. Miocrocontrollers

The robot is run by several microcontrollers. Each microcontroller board has one PIC18F4550 microcontroller and an inter board communications system. Each microcontroller is programmed for a different task. One is a master unit that oversees the communications between the other units. Different units control the vertical or horizontal thrusters. Other units can be added and programmed as needed. In the current configuration there are 5 microcontrollers for; Master control and depth, Thruster control, Sonar, Accelerometers and remote control.

B. Internal Communications

The communications between the units uses a one wire star connected system. All units are wired together and each unit has its own address. The master unit will talk to each unit in turn and either ask for information or distribute that information. The microchip's LIN MC201 communications IC used allows serial communications to be use from the microcontroller. The microcontroller used allows 9 bit serial communications. The current protocol uses the 9th bit to indicate the first byte in a packet which is the destination address. The second byte is the size of the remaining data in bytes. The remaining bytes are the data bytes. This is a reliable and robust system used over very short distances so no error checking is needed or used.

C. Motor Control

Each thruster has a motor controller that controls the thruster's power using Pulse Width Modulation (PWM). One unit, as described above, controls the vertical thrusters which, in turn, control the robots depth. This unit also controls the two horizontal thrusters. These thrusters, mounted on each side of the robot, manoeuvre the robot with differential steering much like a tank. They allow the robot to go forward, backward and turn. Sideways movement is not possible.

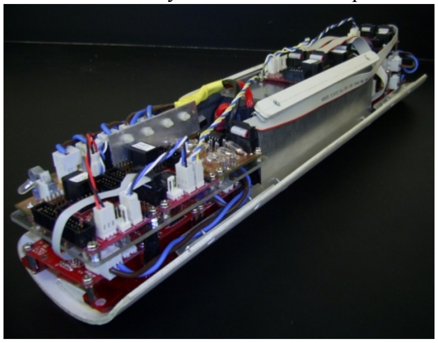

Figure 9 Electronics bay

D. Inter Robot Communications

In order to make the robots as versatile as possible, inter robot communications is required. As the robots are close together, radio was considered. It was found that XBee Pro 2.4Hz modules could work underwater to a distance of at least 25 feet in a depth of water of at least 9 feet. Figure 10 shows the signal strength verses the distance between the antennas (in feet) at various depths. The best signal strength has a value of 0 and the worst viable signal strength is -104. During the radio experiment all packets of information transmitted and received with 100% accuracy.

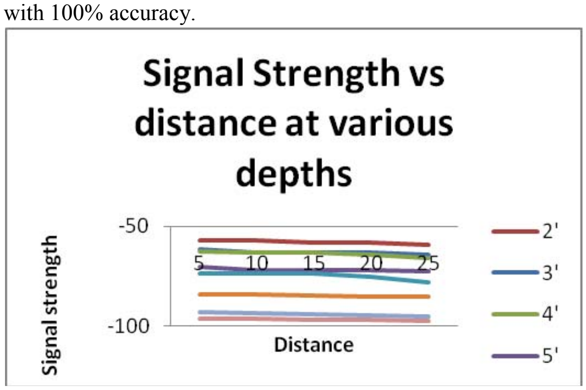

Figure 10. Xbee Pro module signal strength underwater

Thus, these XBee Pro modules are used to allow the robots to communicate with each other. This in turn, allows the robots to perform operations together and to act as a unified swarm of robots.

VI. Sensor Suite

In order for the robot to operate on its own it requires a series of sensors to learn about its environment and its location in it. First and foremost it must be able avoid any possible chance of a collision. Next, if it is to operate on its own, it must know it position and orientation in its environment. These two requirements form its basic sensor suite.

Once the basic sensor suite is in place, the experimenter is free to place many different types of sensors into the robot to gather the information required or to interact with its environment.

A. Basic Sensor Suite

This set of sensors is described in greater detail in Serna, et al. .[8]

1) Collision avoidance

To perform object detection, and hence, collision avoidance, sonar can be use. Sonar is currently quite costly. A simple echo sonar unit alone can be from USD$2000 upwards. There is however a commercial unit used by fishermen to find fish that retails at under USD$30. This unit, the SmartCast made by Humminbird, can be modified to create an echo sonar unit with a range of 30m.

The sonar units were tested by driving the robot down in a 9 foot pool and recording the sonar record to the bottom and the depth from a pressure sensor. The results are shown in Figure 11. (The depth is in feet from the water's surface).

The depth reading was a value of pressure has been converted into feet. The sonar reading is a count of the time it takes an acoustic pulse to travel to the bottom and back. Hence the larger the sonar values the greater the distance to the bottom.

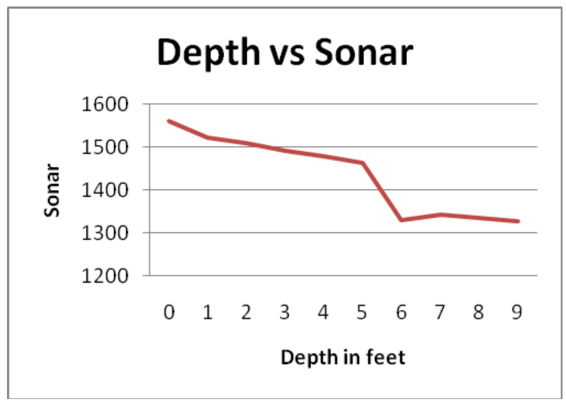

Figure 11 Sonar reading vs. measured depth

As can be seen the readings are not reliable within 4 feet of the bottom. By taking the averages over at least 10 samples gives a result that is good enough to use, especially for sensors that cost so little.

2) Localisation

The simplest way to determine one's position is with a GPS unit or a differential GPS if accuracy is required. Unfortunately, GPS does not work underwater, so a different approach is required.

The approach chosen was a dead reckoning system using a 6 axis Inertial Measurement Unit (IMU).

This system is cost effective but does have a couple of flaws. It needs a known initial location so that it may determine its subsequent locations. It is also prone to accumulative errors.

If the robot is being operated outdoors then the robot could be allowed to rise to the surface at any time to get a GPS fix and then submerge again to continue its mission.

a) Kinematic and Dynamic equations

The absolute position of the robot is described by the three coordinates (x_o,y_o,z_o) of its center of mass with respect to an earth fixed inertial reference frame [8].

Its attitude is described by the three Euler angles (ϕ,θ,ψ).

ϕ : Roll angle $-\pi/2 < \phi < \pi/2$
θ : Pitch angle $-\pi/2 < \theta < \pi/2$
ψ : Yaw angle $-\pi < \psi < \pi$

BODY AXIS ORIENTATION EQUATIONS

We will use the Euler angle relationships, with the Euler angles (flat earth assumption) from the transformation from the local horizontal to the body axes.

$$(\dot{\phi},\dot{\theta},\dot{\psi}) = M(\phi,\theta,\psi)\,\omega(p,q,r) \quad (1)$$

where:
$\omega(p,q,r)$: angular velocity expressed with respect to a body reference frame
$M(\phi,\theta,\psi)$: relation matrix
The resulting matrix equation is:

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix}1 & \sin\phi\tan\theta & \cos\phi\tan\theta\\ 0 & \cos\phi & -\sin\phi\\ 0 & \sin\phi\sec\theta & \cos\phi\sec\theta\end{bmatrix}\begin{bmatrix}p\\ q\\ r\end{bmatrix} \quad (2)$$

The absolute velocity $V_o(u_o,v_o,w_o)$ with respect to an earth fixed inertial frame is the derivative with respect to time of the position (x_o,y_o,z_o) and is given by:

$$V_o(u_o,v_o,w_o) = (\dot{x}_o,\dot{y}_o,\dot{z}_o) \quad (3)$$

BODY AXIS NAVIGATION EQUATIONS

The position, of the robot relative to the Earth, is found by integrating the robot's velocity along its path, or by representing the velocity in Earth-fixed coordinates and integrating each component. The relation is given by:

$$V_o(u_o,v_o,w_o) = R(\phi,\theta,\psi)\,V(u,v,w) \quad (4)$$

where:
$V(u,v,w)$: absolute velocity expressed in a body fixed reference frame.
$R(\phi,\theta,\psi)$: rotation matrix
The resulting matrix equation is:

$$\begin{bmatrix}\dot{x}_o\\ \dot{y}_o\\ \dot{z}_o\end{bmatrix} = \begin{bmatrix}\cos\theta\cos\psi & \cos\psi\sin\theta\sin\phi - \cos\phi\sin\psi & \cos\phi\cos\psi\sin\theta + \sin\phi\sin\psi\\ \cos\theta\sin\psi & \sin\theta\sin\phi\sin\psi + \cos\phi\cos\psi & \cos\phi\sin\theta\sin\psi - \cos\psi\sin\phi\\ -\sin\theta & \cos\theta\sin\theta & \cos\theta\cos\phi\end{bmatrix}\begin{bmatrix}u\\ v\\ w\end{bmatrix} \quad (5)$$

BODY AXIS FORCE EQUATIONS

Using the Newton's law about the center of mass one obtains the dynamic equations for the UAV.

$$\dot{V}(u,v,w) = \frac{1}{m}\sum F_{ext} + \omega(p,q,r)\times V(u,v,w) \quad (6)$$

$$J\dot{\omega} = -\omega(p,q,r)\times J\omega(p,q,r) + \sum T_{ext} \quad (7)$$

where:
m: mass
J: inertia matrix given by:

$$J = \begin{bmatrix}Ix & 0 & 0\\ 0 & Iy & 0\\ 0 & 0 & Iz\end{bmatrix}$$

B. Advanced Sensors

The robot is now almost ready to be used in different experiments and missions. What it now needs are the tools with which to operate. The choice of tool or sensor depends on the mission's profile. The possible include, but are not limited to the following:

1) Camera

The first and obvious senor to be added to the robot is a still or video camera. This can be used by on board systems to analyse the environment or, can send images or video to an external computer.

2) Water Quality

Sensor packages are available that will measure water temperature, saltiness and pH.

3) Compass

Electronic compasses are available that will aid in yaw correction and navigation.

4) Magnetic Anomaly Detector (MAD)

MAD devices, also called metal detectors, can be used to detect ship wrecks, downed planes, divers and ore deposits.

5) Active Sonar

Although the robot already has active sonar it is the simplest type. Other type of sonar, including sidescan sonar and multiarray sonar can be use to create an accurate 3D map of the surrounding seabed.

VII. CONCLUSION

To summarize, the robotic platform must be highly maneuverable and thus requires at least 5 thrusters mounted both vertically and horizontally. It requires a sealed power supply that should last at least 2 hours. An internal navigation system is a must so that the robotic platform can locate itself and maintain position and a communication system to share that position with other robots in the swarm. It finally required a sensor suite to learn about and interact with its environment

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