Toniwha-bot: Towards Energetically Autonomous Marine Sensing

Fred Stinchcombe*, Ian Horsfield, Eoin O'Keefe[+], Chris Melhuish and Chris Irgens

Intelligent Autonomous Systems Engineering Laboratory, Faculty of Engineering, University of the West of England, Coldharbour Lane, Bristol BS16 1QY, UK

[+]Multifunctional Materials Department, Mechanical Sciences Sector, Future System Technology Division, DERA Farnborough, GU14 0LX, UK

*Email: Fred.Stinchcombe@uwe.ac.uk

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Abstract
This paper reports on current research into the design and construction of a small energetically autonomous marine robot designed for sensing applications. The robot is designed to obtain its energy from undersea currents because in this domain the reduction of overall power consumption is vital. It was recognised that the energy derived from the environment would not be sufficient to drive the robot directly, so this 'trickle' of energy would first need to be accumulated in a reservoir. Therefore two methods of energy storage were investigated. We have constructed a spherical robot capable of active vertical motion via a syringe driven by a low powered motor. We propose to derive energetic autonomy via a 'frond' like array of piezoelectric material, which is used to trickle charge the robots secondary power source.

Introduction

1. Background

Over the past few years, there has been considerable interest in developing autonomous underwater vehicles that can function in marine environments with and emphasis on the extension of mission durations [1,2]. Current designs of autonomous underwater vehicles (AUV) tend to be large torpedo-shaped devices driven by turbines; these devices generally have very high power payloads in the region of 600W of power [3] and therefore low mission durations. Current AUVs are also susceptible to marine fouling if deployed for any length of time. The paper therefore addresses the problem of clean marine energy generation for increased mission duration. If the AUV is required to communicate gathered data to the surface a tether or fixed cable is always required if any fast communication is needed. The use of acoustic modems is not an option since these devices tend to be large in dimension, have high operating voltages and consume large amount of power to transmit data [4]. The paper is divided into five sections. The second section of the paper covers the overall design of the robot; this section includes the details of the robots buoyancy control system via a syringe driver. The third section of the paper covers the energetics of the robot and includes a report on the initial research into using piezoelectric film as a means of achieving energetic autonomy, also included in this section is a description of the secondary power source for the robots. The fourth section covers the direction of further research, which will allow multiple robots to be deployed as a group and through the use of inter-robot communication form a community [5] capable of exploiting the benefits of collective sensing and this section will also discuss some of the problems associated with extended undersea missions paying particular attention to current research into the methods available to counter the problems of marine fouling by marine organisms.

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2. Robot Morphology

The prototype of the robot has been constructed from the shell of a plastic bath toy, a bath toy was chosen due to the requirement for the device to be sealed watertight. The plastic outer casing of the toy is satisfactory for the proof of concept model since during testing the device does not have to operate at a depth greater than 1m.

Figure 1 displays the Toni-wha with the motor in place above the syringe barrel, from this diagram it can be seen that the majority on the space within the robot is to be taken up by the syringe driver and its gear train.

2.1 Active motion

The robot moves actively by employing a syringe driven by a low powered motor, this syringe displaces the water accumulated within the syringe barrel thus altering the buoyancy of the robot.

Figure 2 displays the Toni-wha with the motor removed from the syringe barrel.

It was necessary to determine the force applied to the syringe driver when working at depth, thus allowing us to determine the force that is required from the motor to alter the buoyancy of the robot.

Given that the pressure applied to the syringe driver is calculated by

$$F_1 = \rho g h \times \frac{\pi d^2}{4}$$

Where d is the diameter of the syringe (in m), h is the approximate depth under water (in m) from this equation at a depth of 1m the force acting on the syringe is 1.95N. For the robot to be able to surface the driver mechanism must be able to apply a force to the piston of the syringe greater than that of the total frictional forces of the piston and water pressure combined. To be able to generate this force the DC motor is required to be geared down and its rotational output converted to a linear one. As the frictional forces of the piston increase with time, due to diminishing lubrication levels, the following calculations consider the maximum deliverable force that the mechanism can provide to the piston. The mechanical losses incurred in each of the different stages of the system are also considered in our calculations since gearbox and leadscrew efficiencies will have a significant effect on the reduction of the total available force.

The DC motor chosen for the prototype was capable of a continuous maximum power output of 0.85W as can be seen from the graph below.

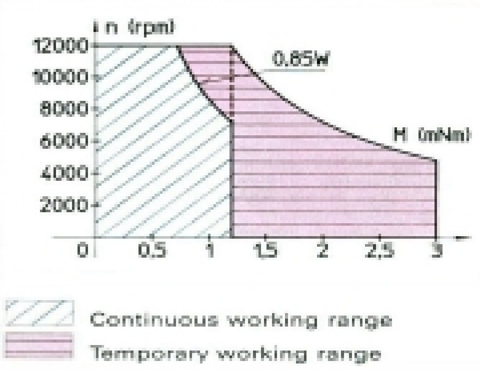


Figure 3. Graph of motor speed in rpm against motor torque in mNm

The equations below shows the relationship between motor power, angular velocity, torque and motor current.

$$P = \omega . T \quad (1.)$$

$$T = Kt.I \quad (2.)$$

So

$$P = \omega . Kt.I \quad (3.)$$

Where P is power in watts, ω is angular velocity in radians per second, T is torque in newton metres, Kt is the motor torque constant in newton metres per ampere and I is motor current in amperes.

Maximum continuous power	0.85W
Maximum continuous current	0.16A
Torque constant	6.8mNm/A
Maximum continuous speed	12000rpm

Table 1. Partial motor specification for the Portescap 16C18-205 DC motor

Using equation 3 and the data in table 1 it can be shown that the maximum continuous power output available from the motor is 1.09mNm at a speed of 7446 rpm. The maximum recommended input speed for the gearbox is 7500rpm.

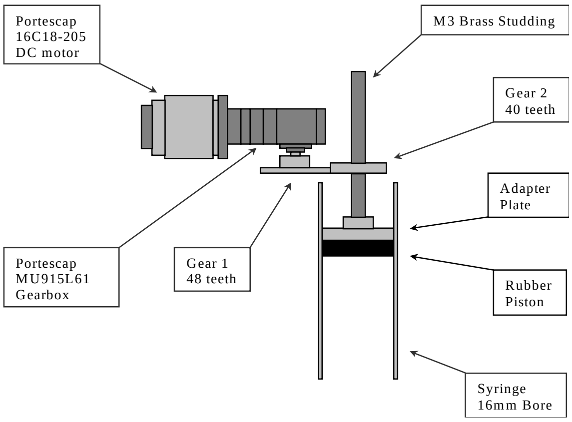


Figure 4. Main constituent parts that make up the syringe driver mechanism

The output torque from the DC motor is applied to the input of the Portescap MU915L61 gearbox as can be seen in figure 4. The purpose of this gearbox is to increase the output torque and reduce the output angular velocity. The relationship between input and output torque is defined below.

$$T_{out} = T_{in}.i.\eta \qquad (4.)$$

Where i equals the reduction ratio 98.7:1 and η is the gearbox efficiency 52%.

The output speed is simply

$$\omega_{out} = \frac{\omega_{in}}{i} \qquad (5.)$$

So the output torque is 55.9 mNm at an output speed of 75.4 rpm. The output shaft of the MU gearbox is attached to a 48-tooth brass gear, which feeds a second 40-tooth gear that forms part of the leadscrew mechanism. The purpose of these gears is purely as a convenient mechanical linkage with an estimated efficiency of η=70%. So the output torque is 32.6 mNm at an output speed of 90rpm.

The final stage of the mechanism is a length of M3 x 0.5mm brass studding and a steel insert at the centre of the 40-tooth gear tapped to match. A brass and steel constructed leadscrew is used to take advantage of the low coefficient of static friction 0.19 between these two materials. The relationship between the torque applied to the leadscrew and the force translated to the piston is derived below.

$$W = F.s \qquad (6.)$$

$$W = T.\theta \qquad (7.)$$

Where W is work in joules, F is force in Newtons, T is torque in Newton metres and θ is angular displacement in radians.

For a leadscrew s is equal to the pitch p in metres and θ is 2π radians. i.e. one turn.

So

$$F = \frac{2\pi.\eta.T}{p} \qquad (8.)$$

and

$$v = \frac{p.\omega}{2\pi} \qquad (9.)$$

Where v is the velocity of the piston in metres per second.

The overall efficiency of the leadscrew is estimated to be in the order of 15% so the maximum available force to apply to the piston is 61 Newtons. Although this is large figure in comparison with the force due to water pressure, the frictional forces of the rubber piston are significant. By the use of different materials and structures in the future, like PTFE rolling sleeves, these frictional forces could be greatly reduced.

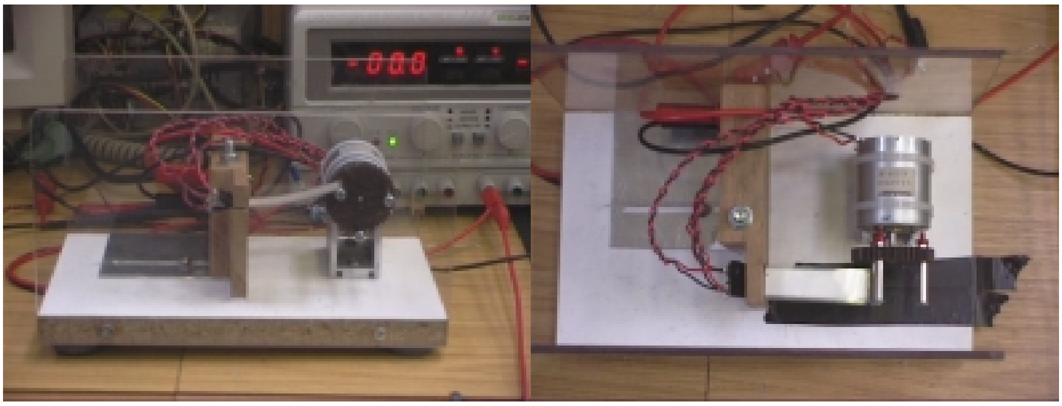
In experimental work carried out with the above design it was possible for the prototype robot to perform 10 dive/surface cycles to a depth of 1m using a standard 9v battery.

3. Energetic Autonomy

The baseline for energetic autonomy is the requirement to generate enough energy to sustain the robot in its most basic function; any generated surplus energy can then be stored for later use. This forces the overall design of the robot to be viewed from the perspective of energy efficiency. This can be achieved through such techniques as the reduction of voltage and operating clock frequency throughout the robot, avoiding unnecessary and wasteful activity and reducing electrical losses inherent in electrical circuits [6].

One method of energetic autonomy currently being investigated is the use of Polyvinylidene Fluoride (PVDF) piezoelectric film. PVDF is a plastic, polymer material that has a thin electrically conductive nickel copper alloy deposited on each side; it exhibits some very interesting piezoelectric properties. It has found widespread uses in the ultrasound industry, due primarily to its flexibility, and the fact that its acoustic impedance is so much lower than piezoelectric ceramics. PVDF has relatively low electromechanical coupling and has a dielectric constant that decreases with frequency, but in spite of all this it remains firmly rooted in the industry as a material of choice for a number of applications e.g. very thin speakers and microphones.

The PVDF film is cut into strips to form a ‘fur’ or ‘frond’ like coating over the top half of the robot therefore the use of a piezoelectric ceramic material would not be suitable for this application. This coating will be used to generate enough power to trickle charge the secondary power source used within the robot. The PVDF material used in the experiment outlined below was supplied as pre-cut strips with electrical connections already attached. To protect the PVDF film it is encased in a protective urethane jacket. PVDF is also moisture resistant and inert to many chemicals making it particularly suited for marine purposes.



(a) (b)

Figure 5(a) shows the test rig that was designed for the testing of the PVDF strips; the strips are displaced via a spinning gear attached to a dc motor. **Figure 5 (b)** shows a top view of the test rig; here the strips of PVDF can be clearly seen being displaced by the bars attached to the gear.

This rig can be used to test different orientations of PVDF film. The electrical energy generated by PVDF material is proportional to the mechanical deformation (stress) placed on the material and intrinsic characteristics of the material. If the force producing the mechanical deformation on the material is reversed, or in the case of our rig, the material 'springs back', the polarity of the output voltage will also reversed. The electricity generated is in the form of a momentary charge when the material is initially stressed. A pieces on PVDF material, 13mm x 24mm x 0.2mm on the rig will generate 20 volts peaks into 3.3MΩ load i.e. 0.12mW. The importance of mechanical as well as electrical phasing can clearly be seen when using the rig.

3.1 Secondary Power Source

It was decided to investigate the use of secondary cell technology as well as the use of large capacitors as a method of energy storage. It was discovered that although capacitors have higher power densities and low internal resistance and are therefore capable of delivering higher peak currents, energy density was of greater importance for this application and therefore it was decided to pursue the use of secondary cell technology.

For many years, Nickel-Cadmium (NiCd) batteries have been the standard choice of secondary cells for small electronic systems. For larger systems e.g. laptop computers and high power radios lead acid or 'Gel Cell' batteries until recently have been used. In response to environmental problems and increased demand alternate technologies were developed: Nickel-metal Hydride (NiMH), rechargeable alkaline and Lithium ion (Li+) secondary cells. Unlike most standard applications the criteria for selection of an appropriate secondary cell technology was not as simple as relative energy density, although this quantity was taken into account. Since the robot may have to wait for long periods of time before undersea currents as strong enough to generate a suitable amount of energy the secondary cells, self discharge characteristic would also have to be taken into account. In the case of NiMH the self-discharge rate is approximately double that of NiCd (about 1% of capacity per day). The main advantage in using NiCd/NiMH cells is that for most applications requiring this type of secondary cell technology is the ability to fast charge the cell, NiCd/NiMH cells ability to accept a 'trickle' of charge would need to be exploited, this method is of course slower but does lend itself well to charging via the piezoelectric film. The last type of secondary cell to be investigated was the Lithium ion (Li+), these cells have a higher capacity than both NiCd and NiMH cells.

Although the advantage of Li+ over NiMH is approximately 10%-30% (when expressing capacity as energy per unit volume), when taking into account the mass of the cell itself Li+ cells have almost double the capacity (expressed as energy per unit mass) of NiMH. This would have to be taken into account when determining the buoyancy of the robot.

The main disadvantage with the use of Li+ cells is their sensitivity to over/undercharging. A Li+ cell must be charged to its maximum voltage to store maximum energy. Also excessive voltage and excessive charge/discharge current can cause permanent damage to a Li+ cell. Unlike NiCd and NiMH cells, which require a current source for charging, Li+ cells must be charged with a combination current voltage source. Li+ cells have a better self-discharge rate (approximately 5% of capacity per month). Its discharge curve has a greater slope then NiMH or NiCd and runs from 4.1v to 3v. Also Li+ cells perform better than most other types of secondary cell at lower temperatures (80% at –20c). In conclusion to the above investigation it was decided that although at first glance the Lithium ion cells provided better performance the associated charging circuitry and the cells sensitivity to charging ruled them out for this application, instead we decided to use a stack of 1.2v 240mAh NiMH Button cells. This would allow us to, given the small dimension of the cell stack, use multiple cell stacks within the casing of the robot.

4. Future Work

4.1 Marine Communications

Further developments to the robot will include the use of two modes of communication, these will be in the form of robot-to-robot communication whilst submerged and robot to base station whilst on the surface. Both methods of communication present their own problems but for the scope of this paper the research to date has only covered the problems concerning undersea communication. The ability for the robots to communicate with each other whilst submerged is being investigated to allow the robots to exploit the emergent properties associated with 'collective' robotics. An example of this would be a single sensor would be able to detect a ships hull passing overhead but if this stimulus were transmitted to a group of sensors, others within the group would be able to detect the same hull and would thus be able to determine its direction of travel and speed. The major drawback with the addition of communication capabilities to the robot would be one of power, thus it will be necessary to limit the communication between devices. The next problem associated with the transmission of information underwater is the transmission media that is to be used for this paper 4 have been considered: -

Fibre Optics links – Although this transmission media would allow a range of up to 1km in open water without the use of signal boosters, since the signal attenuation is about 30dB per Km, the main drawback would come from the possible use of the sensor in shallow waters where snagging of the optic cables would become a major concern.

Wires – Thin wires could be used as a low-tech means of inter-robot communication but the data which could be sent would be extremely limited and since wires are prone to greater signal attenuation the maximum transmittable distance would be a lot smaller. Although this mode of communication would need far less in the way of electronics to back it up it would suffer from the same problem as above with snagging etc.

The above two approaches can also be discounted on the grounds that the robots should be free to drift and should not be fixed to each other.

Sonar – There are a number of different sonar techniques which could be developed for inter robot communication. Parametric sonar, where broadband high frequency signals are produced which in turn form broadband low frequency signals through the water by parametric induction [7], the use of this method would dramatically increase the AUV in size and power consumption. The use of lower power 'primitive' sonar i.e. the use of simple series of 'clicks' could be investigated although a suitable transmission protocol would have to be constructed for this type of communication.

Optical- it is possible to transmit data as pulses of light directly through seawater, this method is similar to optical fibre transfer but does not require the optical fibre cable. However this method is susceptible to beam attenuation problems mainly due to particulate matter density and the photo adaptive state of chlorophyll bearing particles in seawater [8].

4.2 Undersea problems

With any device placed within the harsh undersea environment there are always many potential problems. For devices with short mission durations most of these can be taken as unfortunate 'accidents' but for a device to have an extended duration problems associated with long spells underwater have to be addressed. Firstly, given that salt water is highly corrosive to most metal objects not protected against salt-water corrosion will not last very long, an obvious alternative is to use plastics but most common thermosetting plastics will not withstand the stresses involve with working at depth. Therefore reinforced carbon fibre composite plastics [9], are currently being researched. These advanced materials can withstand large stresses whilst still being resistant to marine corrosion whilst also incorporating devices such as strain gauges within the composites matrix. Of the metals Titanium with high strength, low density and extremely high resistance – even immunity – to most mechanisms of marine corrosion makes this an ideal material for long term AUVs. Another problem associated with long undersea missions is that of marine fouling, there is a vast array of marine organisms capable of marine fouling living in the world's oceans [10]. Adhesion of these organisms to the hulls of sea going vessels is an ancient problem that continues to trouble us today [11-13]. Type and numbers of native fouling organisms is dependent upon a number of characteristics such as water temperature, salinity, clarity and micronutrients in the water. Assorted species of hard and soft fouling need to attach themselves permanently in order to mature and reproduce, and they are attracted to marine structures, ships hull etc for this purpose. For this project the addition of unwanted weight in the form of marine fouling will be of much concern since it will affect the robots ability to alter its buoyancy and rise to the surface.

5. Discussion

This paper reported on the current state of research into the design and construction of an energetically autonomous marine robot to be used in sensing applications. The design details for the construction of the robots buoyancy control by employing a syringe driven by a low powered motor were also reported. It was shown that active vertical motion can be achieved using this syringe pump driver and the prototype was able to perform 10 dive/surface cycles. From the calculations carried out on the syringe driver motor it was discovered that the driver system should be capable of sufficiently altering the buoyancy of the robot to a depth of 10m. This has yet to be confirmed on the prototype

The paper also reported on the early stages of research into a simple mechanism to convert mechanical energy in the form of undersea currents into electrical energy using a 'frond'-like array of PVDF film, some details of the test rig were given. This arrangement will be extended through further research to include a more efficient system. It was recognised that the energy derived from the environment would not be sufficient to drive the robot directly, so this 'trickle' of energy would first need to be accumulated in a reservoir. Therefore two methods of energy storage were investigated, the use of capacitors and secondary cell technology. This accumulation of energy could then be released to provide sufficient power to drive the syringe pump driver mechanism. Work continues on both of these themes.

Within the constraints of power efficiency the paper further speculated on how groups of these robots might be employed to function as a collective sensing array using purely local communication.

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