Biomimicry Methodologies for the Design of a Guidance System for Unmanned Surface Vehicles

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Abstract. The development of autonomous vehicles to perform tasks like detection of unexploded ordnance, search for undersea wreckage and environmental monitoring has gathered momentum in the last decade. As a result, the knowledge perceived was implemented to unmanned surface vehicles (USVs) to perform chemical plume tracing and it has received an increasing interest from the research community in the recent years. The effect of global warming is one of the major concerns in the world today. The UK is one of the key players, contributing its part to reduce the effect on its ecosystems. University of Plymouth has developed its own USV named *Springer* which was tested for environmental monitoring and pollutant tracking. Earlier guidance system of the *Springer* was based on waypoint trajectory. This paper designs a new guidance system of the *Springer* system based on biomimicry imitation. The fuzzy logic is used to imitate the behaviour of bacteria for tracking the source based on either temperature or chemical gradient. A simulation environment with state-space model of the *Springer* system is utilised to show the effectiveness of the approach for obtaining an automatic guidance system for Springer's movement in the unknown environment.

1 Introduction

Bio-inspired engineering is engineering that takes inspiration from nature. There is a constant zeal for engineers to design new materials, structures, mechanisms, and processes. The new products and artefacts to be designed need new ideas. Engineers are flourishing towards bio-inspired engineering as a guide that looks to nature for new ideas. Nature as a mentor has always been a source for concepts that can be mimicked. Thus, bio-inspired engineering is sometimes referred as biomimetics. Biomimetics is a tool that involves the drawing out of good designs from nature. Its activities are multidisciplinary and employ researchers from the fields of biology, material science, chemistry and engineering, who exploit ideas from nature and work collectively to design new smart materials or structures to achieve specific tasks. Hence, it is essential for the engineers to take inspiration from nature than to mimic them directly from nature.

The use of biomimicry to trace chemicals has gathered interest and many of these author's ideas from animals have implemented to trace the chemicals in water (Naeem et al, 2007). Bio-mimetic approach is in the development mode and is gathering momentum in marine research field. The movement of the vehicle would be based on chemical gradient locating the source (Chemical). A number of plume tracing strategies inspired by insects, lobsters and bacterium are being studied and some of them have been implemented recently (Naeem et al, 2007). As there is diversity in application, the strategy inspired by the bacteria is imitated for design of guidance. A biomimicry sensor model using simulink (www.mathworks.com) will

be developed to produce continuous gradient difference based on the vehicle position. This gradient difference is then fed back to guidance to maneuver the vehicle towards the source.
Bacterium makes the use of the gradients of chemical signals released from nutrition (food) sources to reach the location effectively. Their search approach can be associated to a straightforward chemo tactic process which comprises of alternating between two behaviours. The first behaviour called 'run' allows the bacterium to swim effortlessly in a straight line in a particular direction; the second behaviour called 'tumble' allows it to reorient arbitrarily in a new direction for the next search. In the non-existence of any concentration gradient, the bacterium executes an arbitrary walk. When the bacterium senses a positive gradient it reduces the frequency of its tumbling leading to a greater run length in the direction of positive gradient. On the contrary, the negative gradient does not have influence on its sinking behaviour. Changing tumbling frequency makes the bacterium move forward towards the direction of the source.

Nature has always been a mentor for human beings: A number of studies have been carried out to understand the odour guided navigation behaviour of insects (Belanger and Wills, 1998; Vickers, 2000). Study on male moths has proved to be flourishing and they are considered the best examples for plume tracing behaviour and how male moths track plumes of the female sex-attractant pheromone, they move upwind towards their source, a sexually receptive female (Belanger and Wills, 1998). It flies in upwind direction when it finds plume of the pheromone.

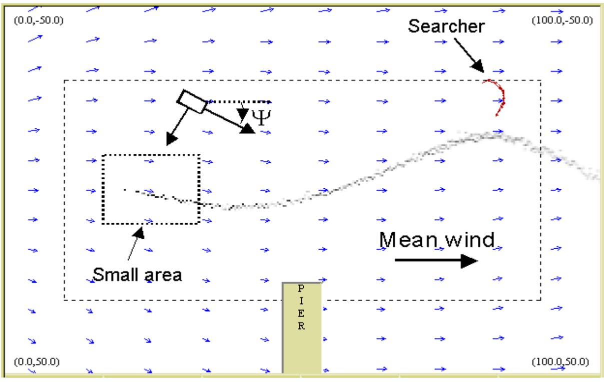


Fig. 1. Depiction of a vehicle (not to scale) performing chemical plume tracing.

The array of arrows in figure 1 indicates the direction and relative magnitude of the flow at the tail of the arrow. The numbers in the four corners are the coordinates of the corners. (Farrell, 2003). This upwind flight is called as 'surging', is highly coherent and is described as follows. If the moth has detected a pheromone plume, the flow of the wind must be bearing the pheromones from the source towards it. As a result, movement against the flow (upwind) will reduce its distance from the source. Always there is a chance of male moths loosing contact with plume due to its patchiness. At this juncture, it stops upwind flight and moves in cross-wind direction to the flow in an intention to re-enter the plume. This cross-wind flight is known as 'casting' in biological terms. Hence the male moths use the approach of steady upwind surges and horizontal castings to locate the source. This strategy was implemented in REMUS AUV by Farrell et al (2003). The AUV operates in a pre-defined region called as operation area (op-area) to detect the chemical. It is engaged to locate a chemical plume, trace the source and manoeuvre constantly towards the source location.

Lobsters have incredible ability of tracing chemical odour; they belong to the family of marine crustaceans and indulge in number of biological activities such as foraging, mating and individual recognition. Lobsters have a pair of antennules located on their head containing chemoreceptor cells. Theories put forward showed that the lobsters flick their antennules at a frequency of 4Hz, this increases the probability of finding the plume and to acquire directional information. They use both the sensor cells located on their antennules and legs for gathering information source (Naeem et al, 2007).

Number of experiments has been done to show flicking of antennules based on initial distance (Grasso et al, 1998; Consi et al, 1994). Lobsters show consistency in behaviour and it steers towards the side of the antenna sensing the higher concentration (Grasso et al, 1998). A definite behavioural change can be seen as they approach the vicinity of the source and the array of chemo-sensors located on their legs helps in locating the source.

A number of USVs project are under construction around the globe and UK is contributed in its own way in research. Young and Phillips (2000) developed a semi-submersible for deploying sensors for ocean surveys. Corfield (2002) developed variants of *Mimir* EV1 for naval and surveying missions and Reed et al (2006) from the United States Naval Academy have published the design of a small mono hull autonomous surface vehicle. Hook illustrated his findings in Hook (2006) on the existing USV types that are recently being developed.

Moreover the list also includes *Springer* USV, which has been designed and developed at the University of Plymouth, UK. *Springer* is an environmentally friendly USV and anticipated to be a cost effective. It is premeditated for handling task like pollutant tracking, environmental and hydrographical surveys in rivers, reservoirs, inland waterways and coastal waters, mostly where shallow waters exist (Naeem et al, 2003). Earlier guidance system of the *Springer* was based on waypoint trajectory. This paper designs a new guidance system of the *Springer* system based on biomimicry imitation based on bacteria. Similarly, as the bacteria follows a chemical gradient to reach the source, a biomimcry sensor model which can generate a continuous gradient is to be built in simulink to simulate the tracking behavior of the *Springer*.

2 Guidance System for the *Springer*

Guidance is the action of determining the course, attitude and speed of the vehicle, relative to some references frame, to be followed by the vehicle" (Fossen, 1994). From the view of control, "guidance is a matter of finding the appropriate compensation network to place in series with the plant in order to accomplish an intercept" (Lin, 1991).

The *Springer* USV was designed as a medium water plane twin hull (MWATH) vessel which is versatile in terms of mission profile and payload. It is approximately 4m long and 2.3m wide with a displacement of 0.6 tonnes (Naeem et al, 2003). It is equipped with onboard sensors to perform multi tasks. Biomimetic guidance to be proposed will be equipped with three simulated sensors C1, C2, C3 which provides chemical concentration at the front side and right and left of the rear of the vehicle respectively.

The vehicle has a differential steering mechanism and thus requires two inputs to adjust its course. It is a two input, single output system shown in figure 2, where n_1 and n_2 are two propeller thrusts in revolutions per minute (rpm). For the vehicle to manoeuvre in a straight line requires both the thrusters running at the same speed and n_d =0 in this case. It is assumed that the vehicle is running at a constant speed of 1.54 m/s for the purpose of linearisation of the model. Hence, it is indication of both thrusters running at same speed. The below equations 1 and 2 shows n_c and n_d representing the common mode and differential mode thrust velocities.

$$n_c = \frac{n_1 + n_2}{2} \quad (1)$$

$$n_d = \frac{n_1 - n_2}{2} \quad (2)$$

n_c must remain constant to maintain constant velocity of the vehicle.

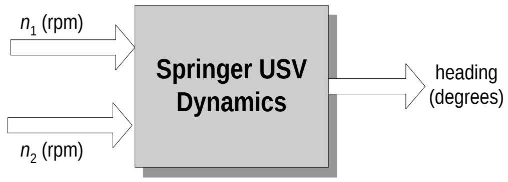


Fig. 2. Block diagram representation of a two-input USV

The dynamic model for *Springer* has already been formatted through the experimental data obtained trials conducted at Roadford Reservoir in Devon, UK (Naeem, 2006). Here n_d has been manipulated and act as the sole input to the system. The differential thrust n_d alters both n_1 and n_2 whereas n_c is maintained constant. Two models of second and fourth order were identified from the data and simulation study revealed that there was no considerable advantage of using a more complex fourth order model. Hence, the second order model shown in equations 3 and 4 in state space form is selected for further analysis and controller design (Naeem et al, 2006).

$$\begin{aligned} \boldsymbol{x}(k+1) &= \mathbf{A}\boldsymbol{x}(k) + \mathbf{B}u(k) \\ y(k) &= \mathbf{C}\boldsymbol{x}(k) + \mathbf{D}u(k) \end{aligned} \quad (3)$$

Where,

$$\mathbf{A} = \begin{bmatrix} 1.002 & 0 \\ 0 & 0.9945 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 6.354\times10^{-6} \\ -4.699\times10^{-6} \end{bmatrix}$$
$$\mathbf{C} = \begin{bmatrix} 34.13 & 15.11 \end{bmatrix}, \quad \mathbf{D} = \begin{bmatrix} 0 \end{bmatrix} \quad (4)$$

The *Springer* movement is controlled with a standard FLC of PD-type with 49 rules designed in Matlab-Simulink. It consists of two inputs error (e) and change in error (de) and a single output which is differential thrust in revolutions per minute.

3 Biomimetic Approach for Guidance

The Vehicle guidance is to locate the chemical plume is based gradient. The USV tracks the gradient of the chemical concentration formed by the dispersion of the chemical by fluid flow.

But the chemical dispersion would not be a smooth gradient due to the turbulent fluid flow. The vehicle can be capsized in a local maxima or minima. There is a risk of the vehicle being trapped in local minima or maxima, if the USV employs a simple gradient following algorithm using the instantaneous sensor information and would be inefficient in tracing a turbulent plume. There is a requirement of a strategy which would generate very recent sensor information and give the vehicle necessary speed and heading commands to guide the autonomous vehicle towards its source. To avoid the local minima trap, this paper uses fuzzy approach for designing the guidance system for Springer.

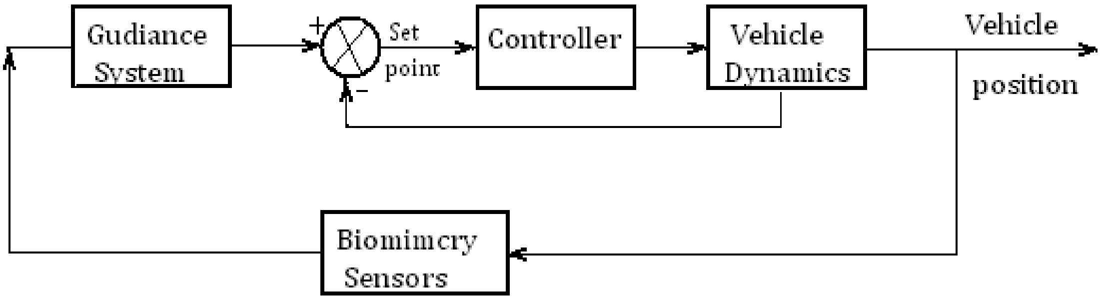


Fig. 3. Biomimetic Guidance, Sensor and Control of *Springer* Vehicle

3.1 Guidance System based on Bacteria

A simple guidance system as shown in figure 3 is developed for the *Springer* model using fuzzy logic rules based on biomimicry imitation. The rules written are inspired from behaviour of bacteria explained earlier. *Springer* vehicle is equipped with three onboard biomimicry sensors as shown in figure 4 which continuously supplies the chemical concentration information at front, left and right positions of the rear of the vehicle. The two gradients one is the difference between C1 & C2 (G1) and another between C1 & C3 (G2) are calculated to manoeuvre the vehicle.

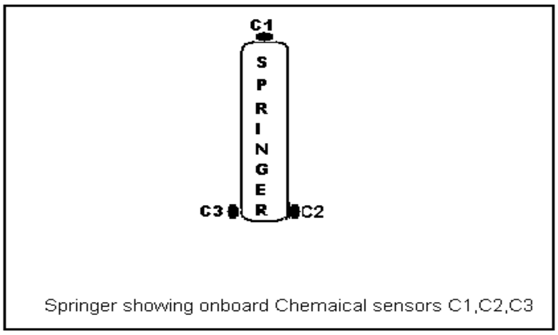


Fig. 4. *Springer* showing chemical sensors

The fuzzy logic guidance system has two inputs G1 and G2. The output of the system is heading angle in radians. The range used for the guidance input varies from [-5 5] both for gradient G1 and G2 and the output range varies from [-45^0 $+45^0$] in radians and 25 rules in Matlab fuzzy logic toolbox were used to simulate the behavior. The surface generated by the guidance system is shown in figure 5 and shows the nonlinearity involved in the waypoints generated based on biomimicry behaviour.

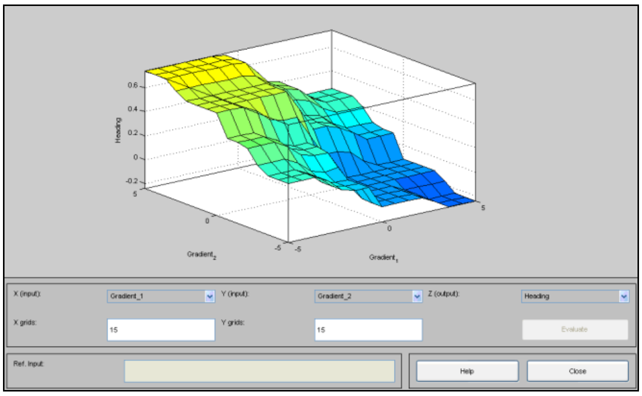


Fig. 5. Fuzzy logic Guidance showing surface generated

The *Springer* vehicle is assumed to be in the co-ordinate system and at a specific starting position (xc0, yc0). The vehicle moves to the next position (xc1, yc1) which is determined by chemical gradient provided by the biomimicry sensors on the vehicle. An exponential distribution of chemical concentration originating from the source has been assumed for simulation purposes. The biomimicry guidance system generates left, right or straight movements for the *Springer* vehicle depending on the gradient produced by the biomimicry sensor. The chemical concentration of C1, C2, and C3 at present position is first calculated in simulated environment to generate the two fuzzy input gradients. These gradients are then used by fuzzy guidance system to generate new waypoint for the controller of the vehicle. Figure 6 shows the biomimicry guidance arrangement for the *Springer* vehicle. The value of U1 in the figure shows the vehicle final position.

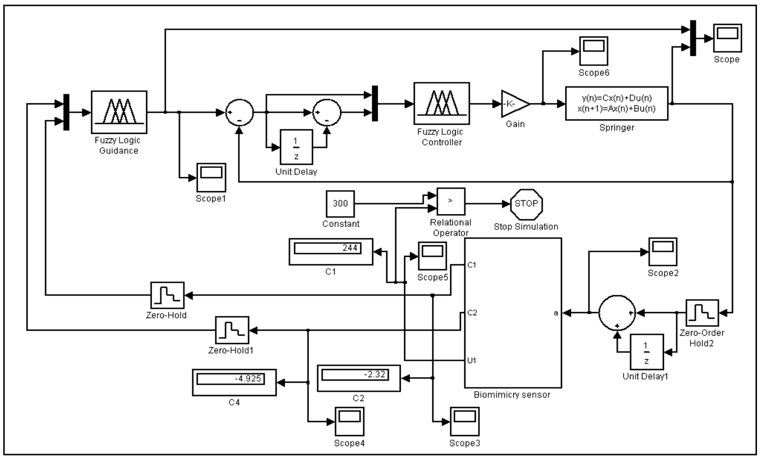


Fig. 6. Simulink block diagram of the *Springer* USV with a guidance system, controller, *springer* and biomimicry sensor

Two cases were considered to show the effectiveness of this approach as explained next.

Case I: The Vehicle is assumed to be at an initial position (50, 50) and the source at (1000, 500).

Figure 7a shows the heading angle generated by the biomimicry guidance system and the vehicle following the trajectory with a small overshoot. The heading angle from the *Springer* is fed to the biomimicry sensor to calculate the chemical gradient at each specific location, as the vehicle manoeuvres towards the source. The simulation result shows the sample time required by the vehicle, before it takes the next heading is 312 sec. The gradient G1 and G2 shown in the figures 7b and 7c are generated by the biomimicry sensor and they are fed as inputs to the fuzzy logic guidance to produce heading for the *Springer* vehicle.

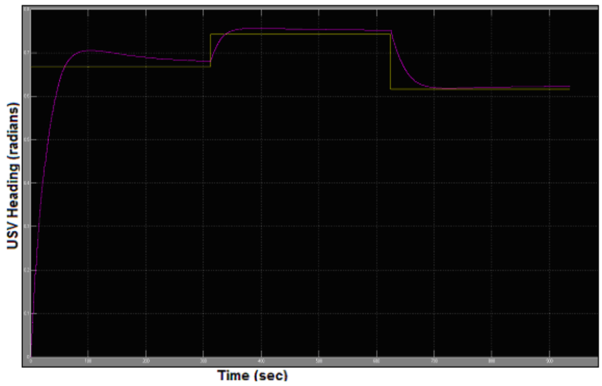


Fig. 7a. USV heading generated by biomimicry guidance

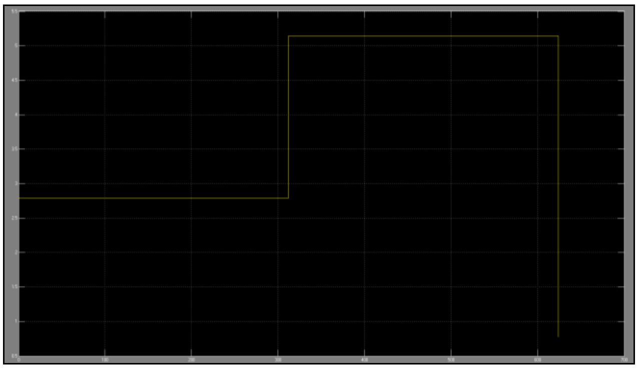


Fig. 7b Gradient G1 generated by biomimicry sensor

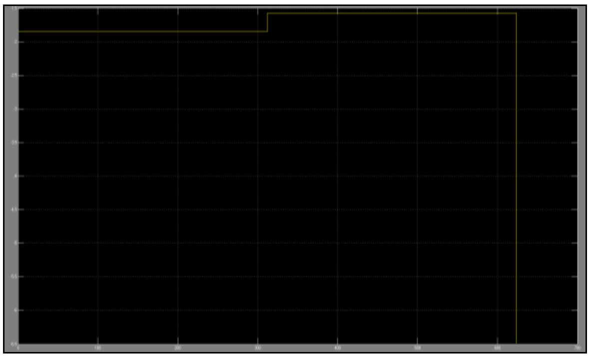


Fig. 7c. Gradient G2 generated by biomimicry sensor

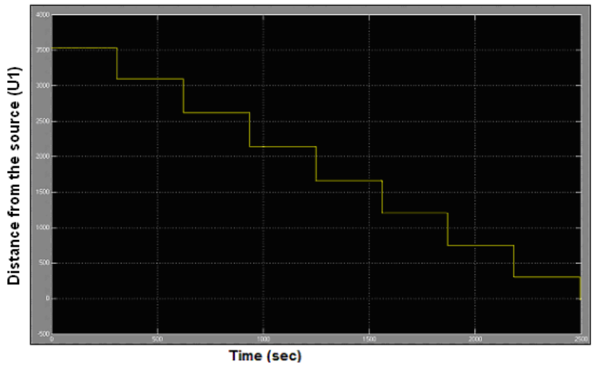
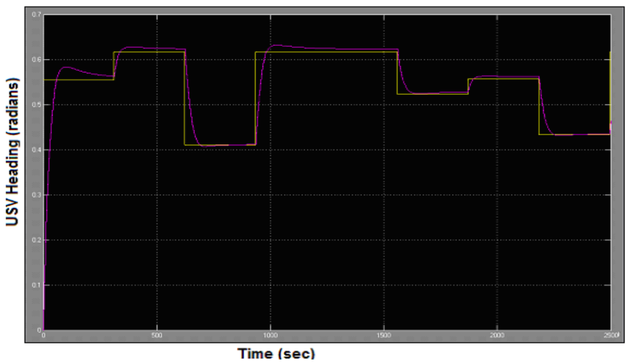


Fig. 7d. USV showing the movement of the vehicle towards the source

The figure 7d describes the vehicle's position from the source of highest chemical concentration and the simulation stops when the vehicle reaches nearer to the source. The figure shows decreasing distance at each sampling and approaching zero and thus arriving near to the source.

Case II: The vehicle initial position is at (400, 300) and the source located at (4000, 3000). Figure 8a shows the tracking by *Springer* whereas figures 8b and 8c depict the chemicall gradient at each location.



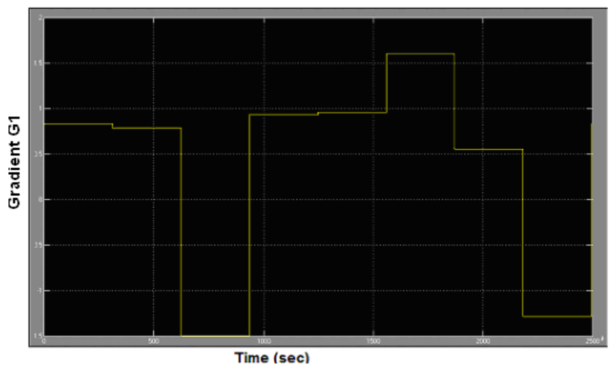


Fig. 8a. USV heading generated by biomimicry guidance

Fig. 8b. Gradient G1 generated by biomimicry sensor

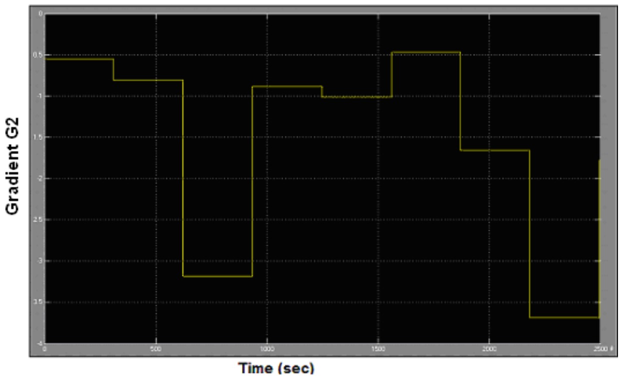


Fig. 8c. Gradient G2 generated by biomimicry sensor

Conclusion:

This paper describes biomimicry methodologies used to design the guidance system of the *Springer* vehicle. Biomimetic approach is followed to track the chemical plume and shows how the vehicle follows a gradient based search to arrive near the highest chemical concentration. The methodology used by the guidance system is inspired from bacteria and biomimicry has again proved that it is not only an inspiration for designing new products but also an effective tool to solve the problem.

Biomimicry sensor modelled generates the chemical gradient for the vehicle guidance to manoeuvre in different direction to reach the highest concentration. It may not be as efficient as the biological counterparts as simulation does not expose the difficulties which can shoot-up with experimentation. Future work will be to apply this techniques in the *Springer* guidance system and to see its viability in real environment with field trials.

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