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Modelling and Control of a Water-based System of Multiple Mobile Robots for Unmanned Rescue

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Abstract: *With the technique from applied engineering and the advent of wireless communication, the nature of rescuing the victims has changed in developing countries where major means of transportation and communication are through rivers using marine vessels/crafts. This paper presents the modelling and control of a water-based system of Multiple Mobile Robots (MMR) for unmanned rescue based on laser optics. The major components of the system prototype are shown unit-wise in a framework. The move-ability and inter-relationships of the MMR are examined along with the use of electronic devices/components described. Performance of the system is discussed, and comparative assessments of the proposed system with other systems are presented in this paper.*

Keywords: *Laser diode, Mobile Robots, Modelling, Control*

1. Introduction

Rivers crisscross throughout the plains of many countries in the world in general and the Asian countries (e.g., India, Bangladesh, and Malaysia, etc.) in particular. The major means of communication of many areas of these countries are through rivers. Therefore, shipping through the rivers is an important method for transportation and communication. In many places, marine vessels carrying passengers and valuable cargo are vulnerable to accidents due to natural causes, mechanical failure, piracy or hijacking. Hence, it is an issue of paramount importance to rescue the victims from the Endangered Boat (EB). In general, two types of approaches are applied to rescue the victims: air-borne vehicle (helicopter/sea-plane), and marine vehicle (manually-driven/automatic). Air vehicle is too expensive in the context of developing countries. Therefore, marine vessel/river-craft shows better efficacy and convenience in the view of economy of such countries.

An unmanned rescue system concerns with many issues and technical disciplines. To deal with so many issues within a limited time, the entire rescue system activities are distributed among the teams consisting of members with expertise in the relevant fields. The activity involves the coordination and communication, and how the data are created and dealt with (Sarker and Tokhi, 2009; Leghari et al., 2008; Zeng, 2003; Becker et al., 2004; MIT, 2011).

With the technique from applied engineering (Klafter et al., 2005) and the advent of wireless communication, the nature of rescuing the victims has changed (Sarker and Tokhi, 2009; Matsuno and Tadakoro, 2004; Dhariwal and Sukhatme, 2007; Liu et al., 2005). This paper presents the modelling and control of a system of MMR, and explains a basis (e.g., sensory circuits, coordination, and math-logic) to support it. The modelling and control of the MMR system is based on laser optics. The construct of the system framework is presented, and the associated experimental results and assessments are discussed in this paper.

2. Problem Formulation

A rescue system, by definition, implies that rescue objects (Boat) will come forward to rescue victims by some sort of mechanism. This naturally leads to the need of representing the system and the mechanism itself.

The philosophy of selecting three Rescue Boats (RBs) is adopted by which a rescue operation can be done. There are several reasons to select three RBs, and few of them are given as: (1) The RBs can easily take control over the EB's surrounding area, for example, three satellites are enough to cover the inter-world, (2) A solid geometric/trigonometric base can be established, (3) On the basis of this trigonometric relation, two RBs can continue rescue operation by considering the third RB as a virtual/dummy RB.

The control and flow of this type of river-craft should execute/operate from a base station. The nearest base station from the risk ship helps the ship at first.

These RBs cannot carry people then; rather they move actively towards the EB after receiving a rescue signal from the base station, detect the EB using sensors, process the sensed data, and form a balanced triangular co-ordination (Sarker and Hussain, 2008; Sarker and Tokhi, 2009), as shown in Figure 1.

Each RB is 1 foot long, 0.5 feet width at the back-end, and 0.27 feet width at the middle front-end (see Figure 2). The three boats are placed in a 20′x30′ (approximately) pond. The EB is placed initially at the center of the pond, later it shifts (left-hand side/ right-hand side/ top side / bottom side of the pond) its position to test the respective shifting positions of the RBs (e.g., not to break a balanced inter-triangular coordination). The computer is set/placed inside the RB (Sarker et al., 2009; Sarker and Hussain, 2008; Leghari et al., 2008).

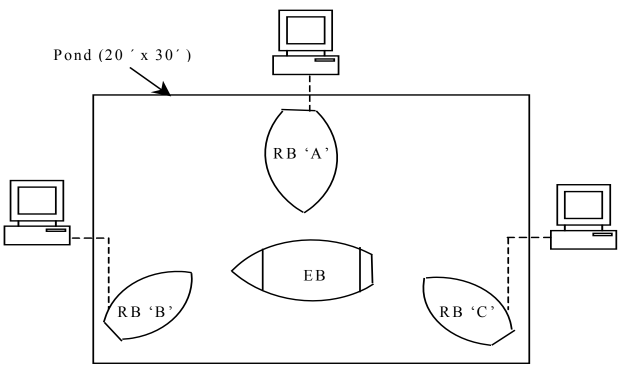

Figure 1. The overall system

Figure 2. An RB with emitter and receiver

The RB-to-RB communication setup is developed laser system to support and to test wireless communication (Matsuno and Tadakoro, 2004; Dhariwal and Sukhatme, 2007; Liu et al., 2005). This laser diode has a higher coverage range 55-60 feet in the free space. Each RB is linked with a particular computer and each computer communicates with one another.

3. Related Works

It is fair to say, that the design engineers are still sceptical concerning the ability of current robot-support systems. A number of researchers (e.g., Sarker et al. (2009), Matsuno and Tadakoro (2004), Dhariwal and Sukhatme (2007), and Liu et al. (2005)) have considered robotic systems. Work in this area is gaining increasing popularity.

Matsuno and Tadakoro (2004) introduced a novel tele-operation method for a mobile robot. They classified the problems in disaster and search-and-rescue processes. Dhariwal and Sukhatme (2007) described a dynamic model of a robotic boat, an algorithm f or estimating its location by integrating sensor inputs, and controller. Liu et al. (2005) introduced a teleoperated robotic boat capable of performing basic movement while feeding back geographical position and video. The previous works paid no attention to a water-based rescue operation.

Sarker et al. (2009) discussed about an advanced control analysis and modelling of a control system for an MMR for unmanned rescue. Sarker and Hussain (2008) presented a simple prototype of sensing and control of a water-based robotic system where initial works on RB relationship, velocity, computer environment and so forth were discussed. Leghari et al. (2008) proposed a model of a multi-mobile robots system where preliminary principles and methods towards an automated system are outlined. The current literature falls short of attention to the use of multiple mobile robots for water based rescuing. To fill this gap and find a solution, the following steps are taken:

- Mobile robotic boat representation paradigm;
- Control analysis;
- Presentation of velocity concurrency and RB relationship;
- Communication and adaptation, including diagnostic; and
- Sensing circuits for operational knowledge and noise.

4. The System

4.1 Framework

The present rescue system consists of three major units: knowledge, control, and data as shown in Figure 3. This section describes important notions of this work.

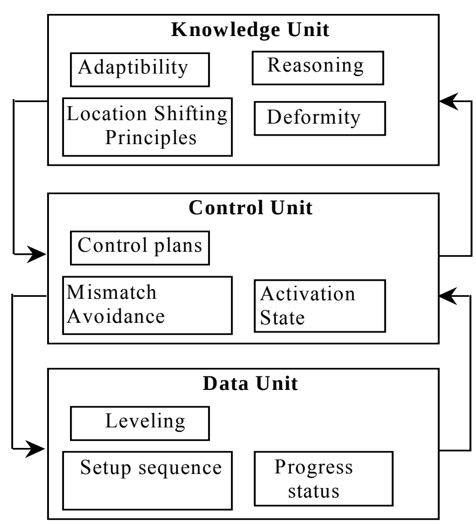

Figure 3. Unit-wise structures

4.1.1 *Data Unit*

The data are sequentially presented in hierarchy as shown in Figure 4. They are arranged in array structures to demonstrate a simple prototype. It governs the stage-change functions to the knowledge sources (KS) to provide an acceptable solution. The RB has a position (e.g., coordination, event.). Coordination is a geometric location of an RB, link draws the relationship of a particular RB to others, and path denotes the affected area. Event implies a physical object with status and time (delay).

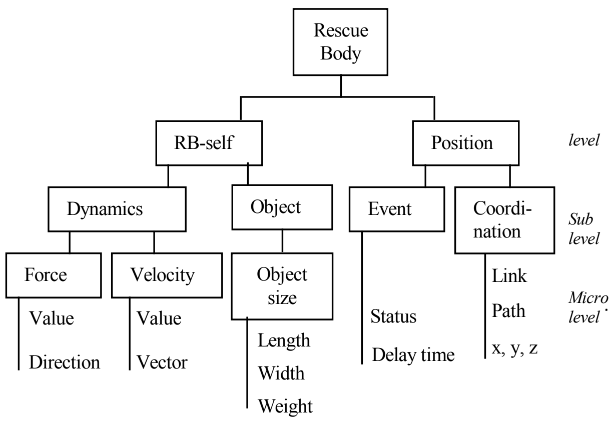

Figure 4. Organisation of data

4.1.2 *Control Unit*

The objective to control a system is to control the outputs in a prescribed manner with respect to (w.r.t.) the inputs via control elements. Two types of control are generally performed: (1) control of Knowledge Source (KS), and (2) control of RB itself. In KS, a special signal (message) is multi-cast to all associated KS when an acceptable decision is made/found, or when there is data shortage. Therefore, no modification is further possible. An automatic controller compares the actual value w.r.t. the reference value. Hence, it determines a deviation and produces a control signal to reduce the deviation. A Proportional-Integral-Derivative (PID) controller has been used for its robustness to develop a balanced I/O relation using the control action(s).

4.1.3 *Knowledge Unit*

It is the origin of knowledge. The KSs can be presented as logical conditions, algorithms, and methodologies etc. KS contributes to the problem solution in the decision making process (Sarker and Tokhi, 2009).

The present framework performs well in the common situation, although the environment changes dynamically. The situation is taken into account one step at a time during shifting position, and reasoning is considered to achieve local situation(s). Hence, the sequence of shifting locations becomes dynamic (Sarker and Hussain, 2008). Location shifting principle determines, for example, a reference frame, parallel /perpendicular to the first frame, parallel /perpendicular between frames and so forth (Sarker and Hussain, 2008).

Deformity is an affliction in which some part of the processing is malformed. Deformity in RB inter-relationship is observed at present. The deformation can easily be controlled by adjusting/rearranging the magnitudes of individual forces using KS. LEAD-LAG compensator has been used.

Reasoning starts with an initial data and continues until the final data are reached when all the involved KSs unanimously share their agreement (or disagreement) about a decision. Figure 5 shows a simple taxonomy on behalf of reasoning because it varies from stage to stage, but the overall goal is the same. Coordination is presented here particularly because mismatch often appears in a balanced rescue operation. Re-allocation is an important step to avoid faulty coordination; afterward modification abates the process to reach in a sound rescue operation (Dhariwal and Sukhatme, 2007).

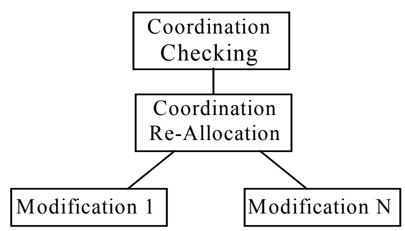

Figure 5. A three-stages of reasoning

4.2 *Control Analysis*

A system consisting of electrical and mechanical variables is called electromechanical system (Sarker et al., 2009; Klafter et al., 2005; MIT, 2011). An RB is an electro-mechanical vehicle that yields a displacement output for a voltage input (an electrical input results in a mechanical output). The linearisation characteristics of a nonlinear object (an RB) can be done by demonstrating the recognised capability of the system. The transfer functions (TF) of mechanical and electro-mechanical models, have been carried out, and input and output variables (e.g., motor torque and RB displacement) have been separated in previous works (Sarker et al., 2009). The outcomes of TFs are to explore Biasing of the MMRs. By definition, biasing is a method of establishing/carrying out some set of operations on behalf of particular applications with a set of goals or motivations. The purpose of biasing is to allow very large co-ordination among the RBs.

4.3 *RB Inter-relationships*

One of the RBs, such as 'B', speeds up and moves more forward, and acts as a team leader when the mission starts after receiving a rescue signal. The 'B' RB detects a safe coordination, exchanges and shares knowledge and information with other RBs for efficient coordination among them. RB ‘C’ takes a position based on ‘B’, and ‘A’ takes a position based on ‘B’/‘C’ whichever is flexible to communicate (Sarker and Hussain, 2008; Sarker and Tokhi, 2009).

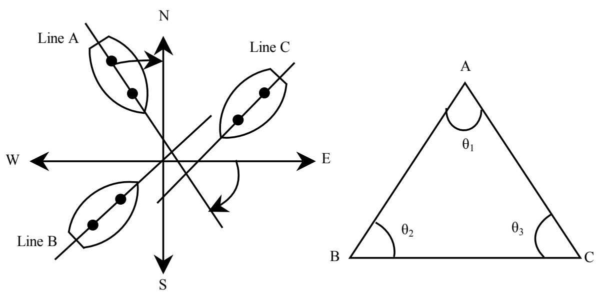

Figure 6. RB inter- relationships

The RB coordinations are dynamic. A triangular relationship among RBs can be established based on geometry as the distances of RBs are known. The line A passes through the centers of RB ‘A’ and intersects the axies. The line is marked/indicated, which can equally divide the RB across the length (Sarker and Hussain, 2008; Sarker and Tokhi, 2009). When the sensor of RB ‘B’ senses a signal coming from an emitter of RB ‘A’, the relative distance between RB ‘A’ and RB ‘B’ can be measured as *d*:

$$d = C\ (t_1 - t_0) \qquad \text{...........}Eq.1$$

where, d–distance, C–light velocity 3×10^8 m/sec, ($t_1 - t_0$) time difference. For example, d = 3m (9.843 feet).

$$AB / \sin\theta_3 = BC / \sin\theta_1 = CA / \sin\theta_2 \qquad \text{..........}Eq.2$$

Equation 2 helps to know the coordination among RBs. For example, if AB and BC are known from equation (1) and if θ_1 is know, then θ_3 can easily be calculated.

The centre of triangle can be evaluated from simulation based on geometrical notion. Therefore, a relationship of forces can be derived from ‘LAMI’ concept, such as, ‘P’ force for ‘A’, ‘Q’ force for ‘B’ and ‘R’ force for ‘C’. From equation 3, an RB can realise its movement (High/Medium/Low) w.r.t. other RB depending on the nature of operation (Sarker and Hussain, 2008; Sarker and Tokhi, 2009).

$$R / \sin\alpha = Q / \sin\beta = P / \sin\gamma \qquad \text{...........}Eq.3$$

The situation of a position and an orientation pair arises so often in robotics, thus an entity called a *FRAME* is defined. Mapping points between frames can be presented as operators, for example, rotate vectors. A rotational operator operates on a vector and changes that vector to a new vector. According to ‘EULER’ angel convention, the relationship of the forces can be expressed on the basis of frames as:

$${}^{K}_{N}R_{Z'Y'X'} = R_Z\, R_Y\, R_X \qquad \text{...........}Eq.4$$

where R means Rotational matrix, subscript and superscript notation K and N mean frame ‘K’ and frame ‘N’ respectively.

In view of spatial description and transformation, the force vector relative to frame example can be simply clarified as shown in Figure 7.

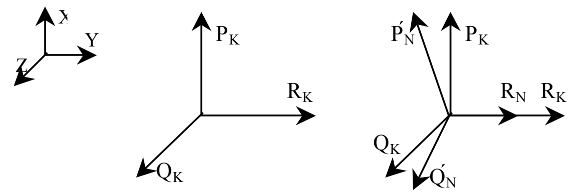

Figure 7. A view of a compound frame

4.4 Concurrency in Velocities

Figure 8 shows a geometric presentation of an RB. A supervisor can monitor the execution of the nominal motion by analysing current situation continuously, adapting it or reinvoking a new plan (Li et al., 2003; Zeng, 2003).

$$u = (v', \delta')\ ,\ z = (v, \delta)\ ,\ p' = \tau(p)\, z \qquad \text{..........}Eq.5$$

v is the velocity, δ is the angle between direction selector and vehicle axis, θ is the angle between vehicle axis and x-axis, and u is the instantaneous value of potential field. p means the present status as shown in Figure 9. It normally implies p = (x, y, θ). (v', δ') is the instantaneous execution of an RB (Sarker and Hussain, 2008; Sarker and Tokhi, 2009).

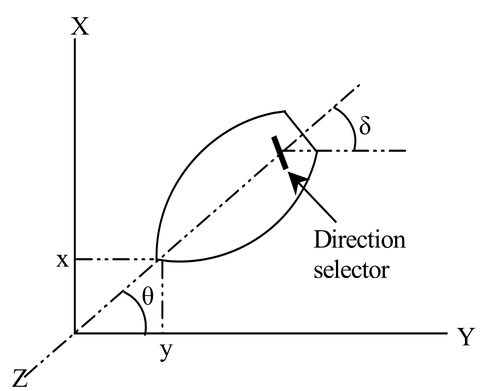

Figure 8. Geometric presentation of an RB

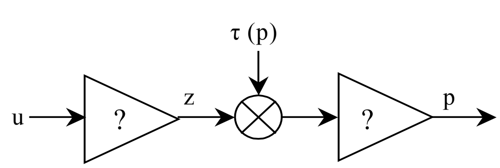

Figure 9. Velocity model: simple scale

The Cartesian velocity (ν_c) vector consists of linear velocity vector (ν). Hence, ν_c with respect to ν can be written as seen in frame 'N' as:

$$\nu_c^{\ N} = [\nu^{\ N}] \qquad \text{……..Eq.6}$$

In this work, Jacobians are introduced that relate object velocities to Cartesian velocities;

$$\nu_c = J\,(x)\,x'$$
$$\nu_c^{\ N} = J\,(x)\,x'^{\ N} \qquad \text{…………Eq.7}$$

where x means displacement, x′means velocity, J means the time-varying transformation.

Jacobian as mapping velocities in X to those in Y as

$$Y' = J(\,X\,)\,X'$$
$$\delta Y = J(\,X\,)\,\delta X$$
$$\delta Y = \frac{\delta F}{\delta X}\,\delta X \qquad \text{…………Eq.8}$$

It can be re-written as:

$$\delta y_1 = \frac{\delta f_1}{\delta x_1}\,\delta x_1 + \frac{\delta f_1}{\delta x_2}\,\delta x_2 + \frac{\delta f_1}{\delta x_3}\,\delta x_3$$
$$\delta y_2 = \frac{\delta f_2}{\delta x_1}\,\delta x_1 + \frac{\delta f_2}{\delta x_2}\,\delta x_2 + \frac{\delta f_2}{\delta x_3}\,\delta x_3$$
$$\delta y_3 = \frac{\delta f_3}{\delta x_1}\,\delta x_1 + \frac{\delta f_3}{\delta x_2}\,\delta x_2 + \frac{\delta f_3}{\delta x_3}\,\delta x_3$$

Each of which is a function of independent variables

$$y_1 = f_1\,(x_1, x_2, x_3)$$
$$y_2 = f_2\,(x_1, x_2, x_3)$$
$$y_3 = f_3\,(x_1, x_2, x_3)$$

4.5 System Electronics

This section describes the step-by-step electronics portfolio of the system briefly. The system is incorporated with laser sensor, voltage regulator(s), voltage converter, zero-crossing detector, amplifier etc. A simple form of an infrared pulse generator (e.g., initially used) is depicted and described in Figure 10. The voltage across capacitor Vc and output voltage Vo are depicted. The system has output of 3 W (peak). The forwarding voltage (Vf) of IR LED is 1.5 volt, the wave length is 800 nm, the pulse frequency is 3 KHz (Sarker and Hussain, 2008).

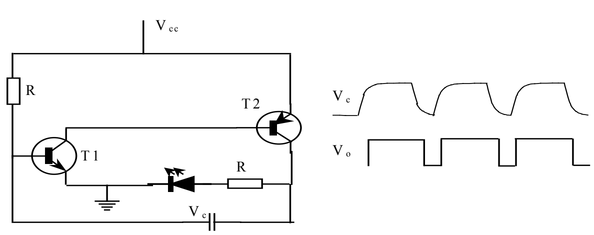

Figure 10. Infrared ray circuitry

Measurement is a process by which physical signal(s) can be converted to a meaningful number(s). The significance of measurement implies to design, to process, and to deal proper operation of equipment(s). Figure 11 depicts the µ second detector that works for reading a short time.

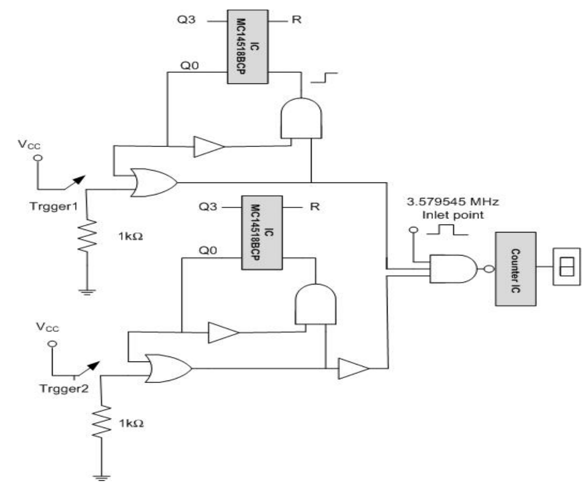

Figure 11. µ second detector

The photodiodes (e.g.; to receive emitted signals) are structured into 4 x 4 orders in a single pattern. The patterns are furnished into array 6x4 orders in a receiver. The receiver panel is placed a quarter foot above the RB floor. Figure 12 shows the laser sensor circuit (e.g.; diode laser ML20A 15-L2 of the Power Technology) used. The power supply is a DC supply (350V-410V). The photodiode is connected with an amplifier, and the amplifier is connected to an oscillator via a high speed switching. The -Vcc is -13V,and +Vcc is +13V.

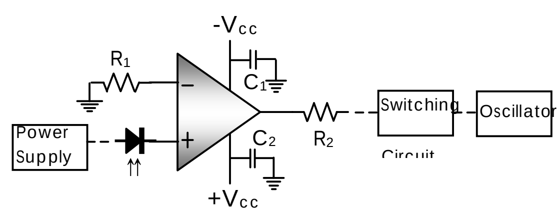

Figure 12. Sensor circuit: simple scale

4.6 Communication Network

Text messaging is an important method to share and to exchange information and it is available on GSM networks. However, GSM performs better in the city/town than in rural area(s) because the mobile phone towers are mainly installed in the city/town (for maximum users) or adjacent to interconnecting roads/highways of the cities. A large proportion of the total length of river(s) passes through villages/rural areas in the south Asian region. Thus, Wireless Local Area Network (WLAN) can be used to overcome the difficulties of the GSM network. Global Positioning System (GPS) is used to know and record the actual geographical positions of an RB (Dhariwal and Sukhatme, 2007; Liu et al., 2005).

4.7 Adaptation

A complex system can be divided into a set of modules at various levels (i.e.; system to sub-system(s) and sub-system(s) to micro-systems(s)) to know whether the system behaves properly or not. As a result, operation mismatch can be detected and resolution can be made easily at micro level(s). Therefore, proper functioning of micro-systems affects subsystems and thus the whole system. Systematic structure of a system representation is needed to deal gently, and knowledge model is denoted as ‘ S ’.

$$S = (RB_1, RB_2, \ldots, RB_n) \qquad \text{……….Eq.9}$$

where RB_n is the n^{th} robotic boat,

$$RB1 = (O_1, O_2, \ldots, O_n) \qquad \text{……….Eq.10}$$

where O_n is the robotic variable,

$$O_1 = K\ (r, I) \qquad \text{……….Eq.11}$$

where K is a constant, r is an operation restriction, I is the Indicator

To share information and knowledge, communication is incorporated in sub-region in a structured manner where each RB follows a communication protocol (Sarker and Tokhi, 2009). The information language (IL), which describes the current situation of an RB, and control language (CL), which updates the knowledge base of an RB are considered in the communication protocol, as depicted in Figure13.

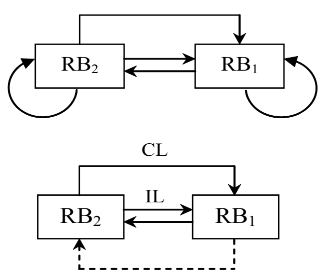

Figure 13. Adaptation process

4.8 Diagnostic

The nature or cause of a state or process is identified through sensors (Sarker and Tokhi, 2009; Leghari et al., 2008). In this process, the data consists of potentially explanatory attributes, for example, event, coordination and so forth. An attribute is explanatory if it is believed that it has some effect on determining the result. Attributes can take on a range of values. In a data process, there are a number of fitnesses, for example, clear fit (e.g., if the data is pure without hassle), rectified fit and so forth.

4.9 Computer Environment and Data acquisition

We use Windows workstations that are connected with Ethernet LAN for an experimental implementation. The multi-tasking functionality and a foreign-function interface is done with the help of a base programming language where Common Lisp Object System (CLOS) exists. The multi-tasking functionality can fork sub-processes, wait for a termination of sub-processes and lock the other process execution. This is necessary for establishing parallel operation within an RB, and for enabling to receive and to handle data coming from other RB. MATLAB 7.0 and C language are used in this work (Sarker et al., 2009; Sarker and Hussain, 2008; Leghari et al., 2008). Band-pass filters and A/D are used for signal processing.

5. Experiments and Discussions

5.1 Noise

A spurious current/voltage extraneous to the current/voltage of interest in an electrical system is called noise. Noise may be generated external to a particular system of interest and enter the system in various forms.

Analogue-to-digital conversion noise – It is a noise, which crept into existence tacitly in A/D conversion. This noise has white effect in general, and its effective value (in volt) can be measured from digital bits pattern (MSB / LSB) in voltage(s).

Intensity noise – It is important to consider the intensity fluctuation of the optical source because it generates noise as a result. It appears insofar observed for two reasons: (i) input voltage fluctuation in the optical source, (ii) wave-length fluctuation for the fluctuation of temperature (strong summer/winter) as described by:

$$\nu_p = \lambda f \qquad \text{…….Eq.12}$$

where, ν_p is propagation velocity, λ is wavelength, f is frequency.

Photo-detector noise – the noise in the photo-detector is a noise of photodiode and a trans-impedance amplifier. The optical source consists of photodiode and a shunt resistor (Klafter et al., 2005; Sarker and Hussain, 2008). Figure 14 shows the photo-detector circuit, whereas Figure 15 depicts the measure of noise versus time.

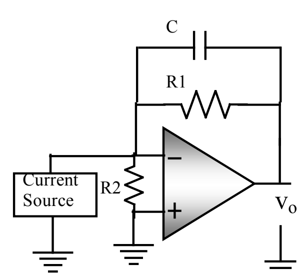

Figure 14. Photo-detector circuit

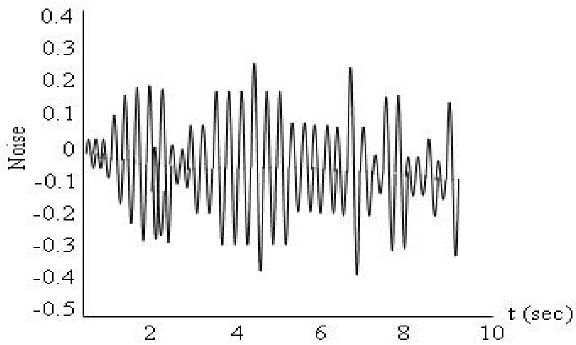

Figure 15. Noise versus time

5.2 Error

Error means the difference between the desired value and the actual output. The velocity of each RB can be measured as:

$$\nu_m = d_{eff} / t \qquad \text{……..}Eq.13$$

where, ν_m is the measured velocity, d_{eff} is the effective distance, t is the time. Figure 16 shows the average output error of the RBs ('A','B','C') at the starting period of RBs coordination. Figure 17 shows the measure velocity of RBs w.r.t. error (in percentage) where RB 'A' and RB 'B' are changing their positions w.r.t. RB 'C'.

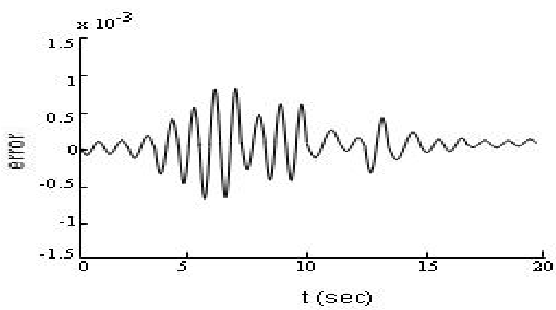

Figure 16. Current error at the starting period

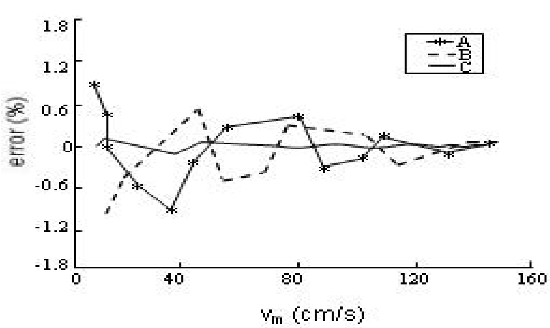

Figure 17. Error versus V_m

5.3 Laser Optics

Laser has good transmittance through fog, invisible to human eye, giving the system better performance under a large range of weather conditions (Sarker and Hussain, 2008). The wave length of laser generally varies with temperature, such as 0.3-0.5 nm/°C. The spectral shown in Figure 18 extends over the range 400 to 1000 nm. Figure 19 shows the voltage level of a receiver.

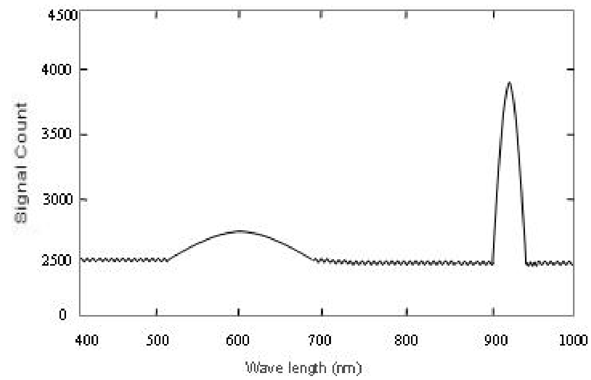

Figure 18. A typical spectrum of laser diode

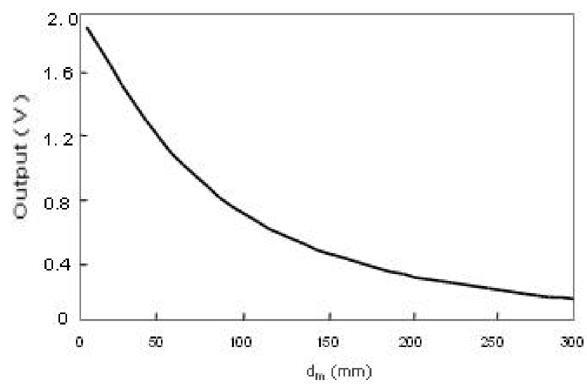

Figure 19. Output versus d_m

5.4 RB Position

Figure 20 shows the relationship among RBs. RB 'B' is considered as a reference whereas RB 'A' and RB 'C' are considered as mobile robots (Sarker and Hussain, 2008).

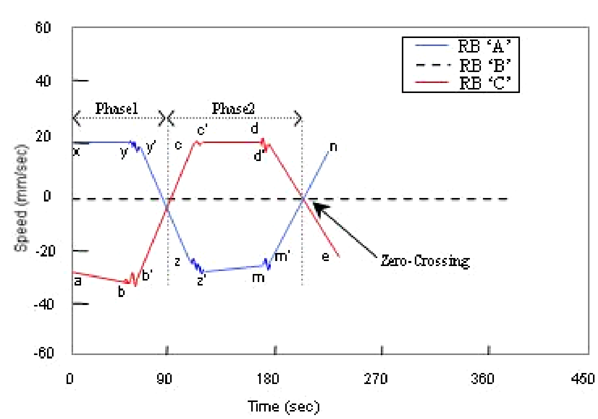

Figure 20. Speed versus time

In phase 1, a balanced triangilar relationship did not form because RB ‘A’ took higher speed than RB ‘C’. In phase 2, both RB ‘A’ and RB ‘C’ had maintained a balanced speed. The speeds of RBs are not linear throughout the moving path (such as a-b, z´-m, c´-d), and pice-wise linear appro-ximation is considered.

Figure 21 shows the rate of coordination (it means inter-coordination in percentage) against noise (in volt). This can be estimated by Equations 2 and 8.

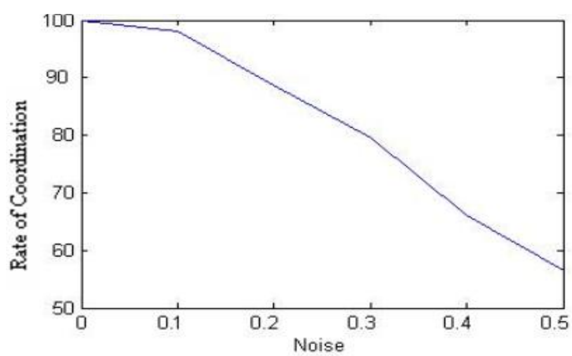

Figure 21. Rate of coordination versus Noise

There are two types of forces in propeller functions: one is radial force (F_r), another is axial force. Axial force (F_a) helps an RB to move in a particular velocity. If, T is the torque, D is the propeller diameter, then F_r can be calculated as:

$$F_r = T / D \qquad \text{………}\mathit{Eq.14}$$

Axial force (F_a) is the ‘cosθ’ component of the radial force (F_r) presented in Figure 22. The positive (+) and the negative (-) values mean that the robotic body (e.g., an RB) moves in the forward and backward directions, respectively.

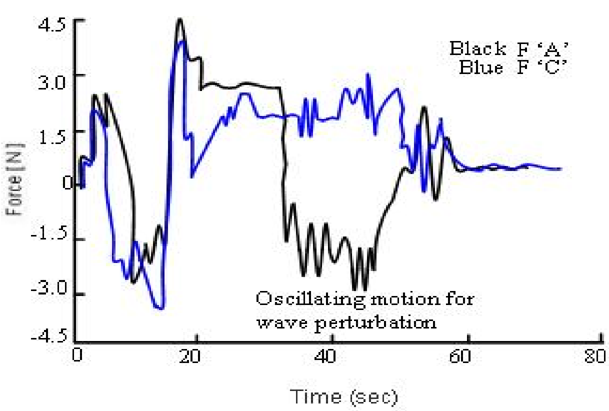

Figure 22. Axial forces in RB ‘A’ and RB ‘C’

Figure 23 presents RB coordinations (%) with respect to time (sec). With reference to Section 4.2, rate of coordination implies - the affordability of each RB in a group is assumed to progress towards the RS at a grouped-proportional speed, or *vice versa*.

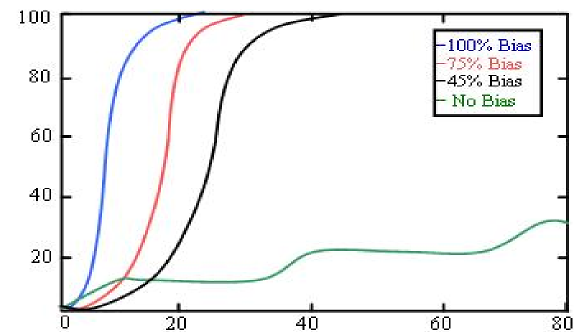

Figure 23. Percentage of RBs coordination versus time

A simple comparison is given in Table 1, where ‘A’ is the proposed technique in the assert work, ‘B’ is the technique proposed by Liu et al. (2005). Expansion mode (Em) means the dimension of presentation, and it is considered as 2^n.

Table 1. Comparison of techniques/concepts

		Expansion Mode (Em)		
		E_m=32	E_m=16	E_m=8
Co-Ordination	A	100%	98.8%	66.3%
	B	100%	79.4%	52.1%

6. Conclusions and Future Works

Having regards shipping through the rivers is an important method for transportation and communication in many developing countries, there is a need to develop a water-based MMR system for unmanned rescue. The general principles of the proposed MMR system have been presented in this paper.

The mobile robotic boat paradigm has been discussed, and the move-ability and inter-relationships of MMRs have been presented. Electronic devices/components used for data has been described. Communication between RBs has been established to share and to exchange knowledge and information. Performance of the present system has been analysed and presented. Comparative assessments of the proposed system with existing literature have been carried out.

There are a number of major research challenges that still need to be overcome before a full potential of the system, for example, necessary steps for laser sensor for summer/winter, development of sophisticated controller, an extensive model to include driving/ steering commands of the vessel and lateral shift due to wave/current perturbations.

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