Multi-vehicles formation control exploring a scalar field

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Abstract

We present a multi-vehicles system capable to climb a scalar field. The vehicle are capable to move in formation, climbing the intensity of a random positioned light source, and either detect multiple light sources, breaking formation in order to direct singularly along a preferred direction, according to the field measure that each of them detect. We use simple and reliable test-bed platforms, communicating through an RF-tranceiver, and directed from Basic Stamp 2 from $Parallax$.

I. Introduction

Multi-vehicle systems are frequently employed in several technological and scientific applications. Control of unmanned vehicles is fundamental where the environment is not accessible or is not suitable to human biology. Starting from this consideration we can briefly give an overview of the different fields of application. We can catalog with respect to the specific topology of the environment, so we can distinguish the different cases between three macro topology: space applications, terrestrial applications, and underwater applications. The three of them may be motivated by either scientific or engineering goals. We can cite, among the others, exploring rovers, AUVs (autonomous underwater vehicles), that have to move and coordinate in an unknown environment and report useful measure in order to reconstruct it. There are several different cases that can describe this kind of logic. In order to generalize from the particular topic applications, we can refer to our multi-vehicle system as a moving sensing platform, able to measure through dedicated sensors, vector or scalar fields that define the circumstanding environment. Selecting a multi-vehicle sensing platform, with respect to a single-vehicle sensing platform present different advantages while balancing the increasing costs of the mission. First of all this kind of choice presents the opportunity to dispose of a redundant system, that is equivalent to say a more reliable system, and furthermore allows, in a shorter time, one to cover a larger percentage of the field that we are interested to measure. Nevertheless those kind of systems allow obtaining differential real time measurements, that obviously allow for better reconstruction of both the space and time dynamics of the field. Our goal is to present a demonstration of a measuring platform constituting three terrestial robots, that move in order to detect and move in the direction of a randomly positioned light source. This simple demonstration can simulate how it is possible to detect potentially dangerous emitting sources, such as radiation, fire, without involving humans within the hostile environments. The logic adopted is simple and can be adaptable to different types of sensors. The case we are going to consider is the detection of a bright light emitting source. This choice was chosen due to the simplicity and reversibility that the luminosity intensity field implies. All the hardware employed is comprised in the Parallax educational kit plus an extra component: the 912MHz RF-tranceiver, from Parallax. The three different platforms are controlled by a BasicStamp2 (BS2) microcontroller from Parallax. This is an inexpensive way to realize our goals.

The rest of the paper is organized as follows. In Section we briefly described our goals and strategies adopted in the project, Section describes the theoretical framework. Section III gives an overview of the hardware environment, and Section **??** gives a brief overview of the costs, and the analysis of the eventual mass-production. Section **??** is left for conclusions and possible improvement to empower future works. In appendix we find the commented PBasic programs.

II. Mission Overview

We present a moving sensor platform composed of three robots. They are planned to move in a cooperative way detecting one or more random positioned random light source. Each platform is equipped of a light detector sensor, a photodiode. The sensing beam of the photodiode has been blinded to reduce the noise coming from external disturbances.

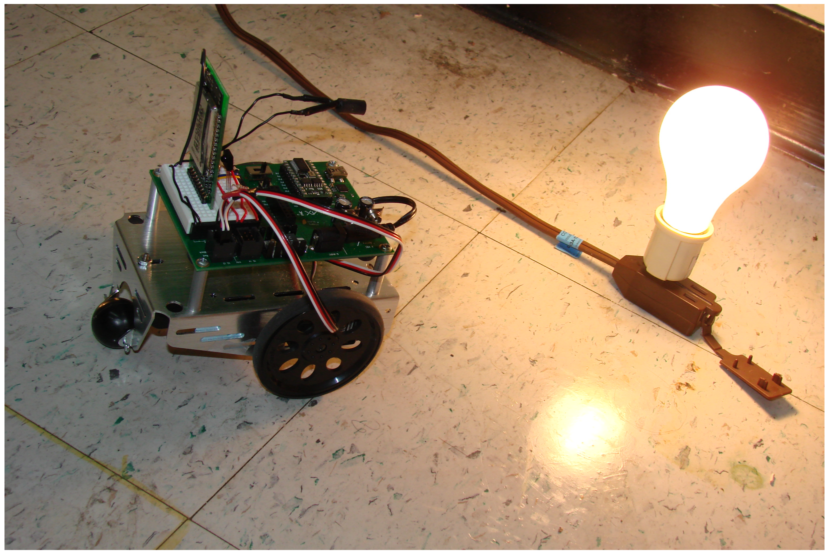

Fig. 1. Vehicle in the neighborhood o f a light source.

The trajectory of the three vehicles is directed by one of the three agent that acts as a master.

The master vehicle, depending on the actual value of measurements that it takes, implements a decision algorithm in order to decide the trajectory and drives the two slave vehicles.

Communication between agents is guaranteed with three RF tranceivers working in UHF-band. Communication is activated by the master vehicle that transmits to the two slaves, assigning to each of them a determined time slots.

The mission comprises two functional modes.

In the first case the master dynamics, governed by a time continuous sensor based controller, force the two slaves vehicles to move in a determined formation. In the second working mode, depending on the onboard measurement from each vehicle, and on the communication network status (operative or not operative), the three vehicles can move independently, each of them capable to implement a decisional algorithm that drives along the desired trajectory.

This last working mode, variant to the master slave protocol previous adopted, can be considered as a safe mode in case of failures on the communication links or on the master vehicles.

III. Mathematical Modeling and Governing Equations

This section briefly explain the mathematical model adopted to derive the motion of the three robots. We adopted some of the tools from classical control theory. As a first hypothesis we reasonably consider the motion of the vehicles plain. According to this, the state vector of each vehicle $\mathbf{x}(t) : \mathbb{R}^+ \to \mathbb{R}^4$ will be composed of four elements, two describing the position vector $\mathbf{p}(\mathbf{t}) : \mathbb{R}^+ \to \mathbb{R}^2$ and two describing the velocity $\mathbf{v}(t) : \mathbb{R}^+ \to \mathbb{R}^2$

$$\mathbf{x}(t) = \begin{bmatrix} \mathbf{p}(t) \\ \mathbf{v}(t) \end{bmatrix} \tag{1}$$

We can briefly report equations describing the entire system behavior for the first working mode as described in Section III.

$$\begin{aligned} \dot{\mathbf{x}}_1(t) &= \mathbf{B}\mathbf{u}(t) \\ \dot{\mathbf{x}}_2(t) &= \mathbf{L}_{1,2}\dot{\mathbf{x}}_1(t) \\ \dot{\mathbf{x}}_3(t) &= \mathbf{L}_{1,3}\dot{\mathbf{x}}_1 \end{aligned} \tag{2}$$

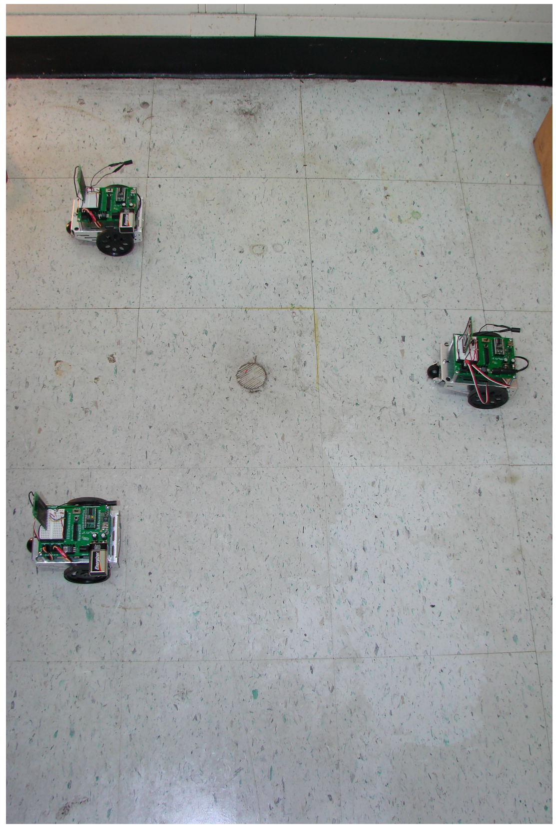

Fig. 2. Multi-vehicle sensing platform.

We now remind the meaning of the single term in equation (2). $\mathbf{x}_1$, $\mathbf{x}_2$, $\mathbf{x}_3$ represent the states of the master vehicle and of the two slaves respectively. The control input $\mathbf{u}(t)$ acts on the master vehicle and is a vectorial function of the scalar measurements $\Phi(t)$: $\mathbf{u}(t) : \mathbb{R}^+ \rightarrow \mathbb{R}^4$, $\Phi \in \mathbb{R}^+$. Since we control just the velocity of the vehicles, we assume the control matrix to be equal to a block diagonal matrix

$$\mathbf{B} = \left[\begin{array}{c} \mathbf{I}_{2\times2} \\ \mathbf{0}_{2\times2} \end{array} \right]$$

The two slaves vehicles are forced to follow the master dynamics according to the value of the element $\mathbf{L}_{1,j}$, with $j = 2, 3$ of the Laplacian matrix. The matrix $\mathbf{L}$ is the time-variant Laplacian matrix for the communication network. We briefly remind the meaning of the matrix $\mathbf{L}$. We assume that the node $j \in V = \{1, 2, 3\}$ represents the j-th vehicle, and the set $E \subseteq V \times V$ describes all the communication links between the vertices $j \in V$. We define the adjoint matrix $\mathbf{A}$, such that each of its elements is defined as: $a_{i,j} = 1$ if the ordered pair $(i, j) \in E$, $a_{i,j} = 0$ otherwise. The Laplacian matrix $\mathbf{L} \in \mathbb{R}^{3\times3}$ is then defined as $\mathbf{L} = \mathbf{A} - \mathbf{D}$, where the matrix $\mathbf{D}$ is a diagonal matrix whose i_{th} entry express the total number of links for the i_{th} node. In our case we consider the Laplacian matrix to be piece-wise continuous respect to time and the communication network to be directional.

We can think to write equation (2) in term of the state vector $\mathbf{X} = [\mathbf{x}_1 \quad \mathbf{x}_2 \quad \mathbf{x}_3]^T$:

$$\dot{\mathbf{X}}(t) = \mathbf{L}(t)\mathbf{X}(t) + \mathbf{1}_3 \otimes \mathbf{B}\mathbf{U} \tag{3}$$

Here the term $\mathbf{1}_3 = [1 \quad 1 \quad 1]^T$ In this case the control input is the vector $U = [\mathbf{u} \quad \mathbf{0}_4 \quad \mathbf{0}_4]^T$. Equation (3) clearly explain that the system we are working with is a linear time-varying system with an open-loop control. We want to notice that the linearity of our dynamics does not imply the linear dependence of the control respect to the measurements $\Phi(t)$. In fact the control vector $\mathbf{U}(t)$ is usually a nonlinear function of Φ: $\mathbf{U}_i(t) = \mathbf{f}_i(\Phi)$.

The second working mode instead is activated whenever the communication links are permanently not working. This is equivalent to state $E = \oslash$, where the symbol $\oslash$ indicates the empty set.
in this case the elements of the state matrix $\mathbf{L}(t)$ will be identically equal to 0. The transition matrix of our dynamical linear system, comprehensive of the states of the three agents, will be equal to the identity matrix, and the response will be governed just from the control input vector. In this case, in order to guarantee the controllability of our system, we impose a different control protocol. This can be applied as a safe mode, in order to guarantee the continuity and the total or partial achievement of the mission goals in case of failures. System (3) becomes in this case:

$$\dot{\mathbf{X}}(t) = \mathbf{1}_3 \otimes \mathbf{B}\mathbf{V}(t) \tag{4}$$

Where in this case $\mathbf{V}$ will be the emergency control input, with all non-zero components driving each vehicle.
As in the previous one, the vector $\mathbf{V}$ will be an opportune function of the measurements Φ taken onboard by each vehicle.

The hardware and software realization of the control will be discussed in more details in the following sections.

IV. Hardware Environment

The hardware implementation we adopted for the moving sensing platform comprises the following components for each vehicle:

- 1 BS2
- one RF-tranceiver (912MHz)
- two servomotors
- 1 photodiode

We also dispose of minor components for the circuitry, such as resistors, capacitors. In the sequel we will describe the functions of each component.

Microcontrollers are versatile central processing units. They can perform simple programmed decision making on many devices at a low-cost to the manufacturer. As such they are very popular among those whom are prototyping robots that need some computing power. The Basic Stamp 2 is one such popular microcontroller from Parallax. It is a basic peripheral interface controller (PIC) 16, which means that the microcontroller has 16 I/O pins that can be used to interface with and program. It has a memory size of 32 bytes; 6 bytes are I/O and 26 variable. This is the amount of memory it has to process around 4000 instructions/second.

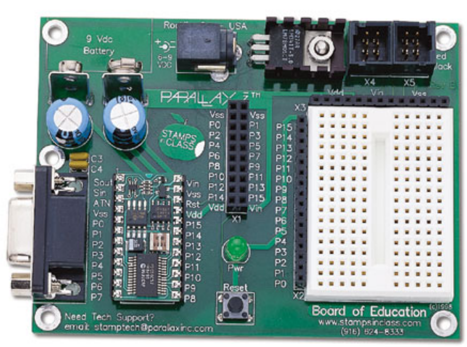

Fig. 3. BS2 Parallax.

The microcontroller also comes with 2K bytes of electronically erasable programmable read only memory (EEPROM); data storage and programming space. Using the PBASIC language, a Parallax derived BASIC computing language, and a serial connection, the microcontroller can be programmed through a personal computer. As such this microcontroller is very user friendly for use in prototyping robots.Microcontrollers are versatile central processing units. They can perform simple programmed decision making on many devices at a low-cost to the manufacturer. As such they are very popular among those whom are prototyping robots that need some computing power. The Basic Stamp 2 is one such popular microcontroller from Parallax. It is a basic peripheral interface controller (PIC) 16, which means that the microcontroller has 16 I/O pins that can be used to interface with and program. It has a memory size of 32 bytes; 6 bytes are I/O and 26 variable. This is the amount of memory it has to process around 4000 instructions/second. The microcontroller also comes with 2K bytes of electronically erasable programmable read only memory (EEPROM); data storage and programming space. Using the PBASIC language, a Parallax derived BASIC computing language, and a serial connection, the microcontroller can be programmed through a personal computer. As such this microcontroller is very user friendly for use in prototyping robots. The BS2 basic stamp from Parallax is not able to perform multiple command at the same time.

The component that allows vehicles to communicate is the RF-tranceiver.
The RF-transceiver is a single unit that is able to transmit as well to receive data. Transmitter and receiver

Fig. 4. RF-tranceive 912MHz Parallax.

are not allowed to work simultaneously. These have been increasingly popular since they allow the user to interface multiple devices with minimal space usage. The Prallax RF-transceiver uses a 16-bit cyclic redundancy check (CRC) error detection where by it takes an input of data stream of any length and produces as output a value of a certain fixed size. This is great for reducing common errors such as noise in the transmit/received signal. It also has a first in/first out (FIFO) buffer where the data received is store temporarily until the microcontroller is ready to take the data. The transceiver has a range of 800ft and a 9600bps serial, which is the rate at which it communicates with the microcontroller. It transmits and receive radio signal in a passband centered at the frequency of 912MHz.

The two of servomotors present in each vehicle works as actuators, controlling the velocity, and consequently the trajectory of the vehicle.
A Servomotor is a particular kind of DC motor that is provided with a feedback position control. This electronic device disposes of an output shaft, that can occupies the commanded angular position, consequently to a coded signal from the motor. This position will be maintained until the signal from the servo will be constant. A variation of the control signal will cause a variation of the actual angular position of the shaft. Servo motors are very common in the robotics word, because of the small ratio that compares their dimensions, relatively small, with the power that they are able to furnish

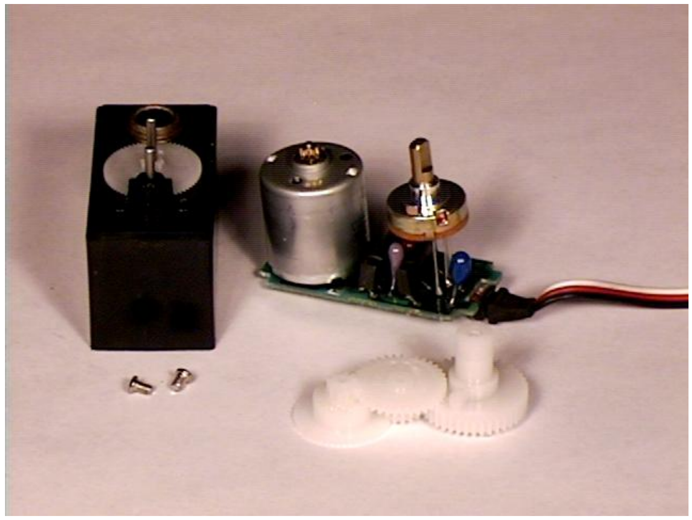

Fig. 5. Servomotors: components.

In Fig **??** is shown the control circuitry, the external case, the gears, and the motor. Servos are interfaced with the external power source, the BS2 in this case, trough three wires of different color: the red one is for the power, typically $5V$, the black one is connected to the ground, and the white one represents the control line A potentiometer connected to the shaft allows to change the angle of the current. Until the circuitry finds that the shaft is not in the correct position respect to the current angle, the motor will rotate the shaft until the equilibrium position.
The angular amplitude estimated for the shaft is communicated trough the control wire. The duration of the pulse sent will determine how far the motor is from the nominal position. This mechanism is called Pulse Width Modulation.
A proportional controller regulate the amount of power absorbed by the motor. The faster it runs, the greater will be the amount of power necessary to work.

The sensor capable to detect the light intensity field is the photoresistor.
A photoresistor or Light Dependent Resistor is an electronic component capable to vary its own resistance according to the intensity of the incident light.

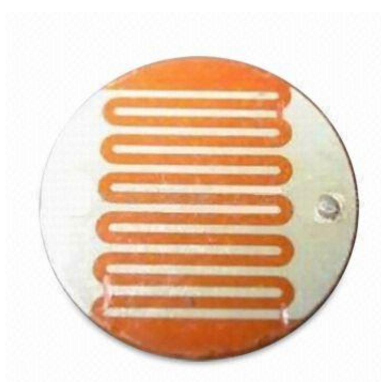

Fig. 6. Photoresistor.

Photoresistors are made of a high resistance semiconductor material. If the light incident the dispositive is a wave of relative high frequency, the radiation absorbed allows the conduction electrons to jump into the conduction band, causing a decreasing in the resistivity of the material.

$$R \propto P^{-\beta} \tag{5}$$

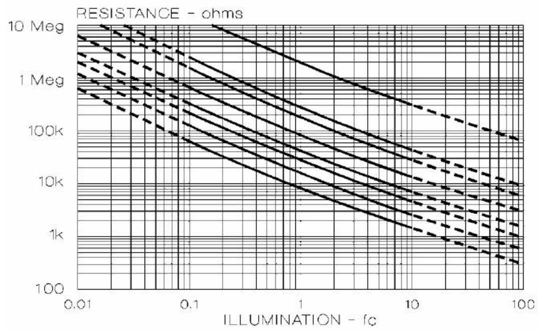

Fig. 7. Characteristic of a photoresistor: resistance vs incident light power.

Where R is the resistance od the component, P is the incident power, β is a constant typical of the constructive material. The photoresistor is employed in an RC series circuit, Fig **??**. The measure of the incident power that the vehicle will elaborate will be proportional to the characteristic RC time of the circuit exposed in Fig **??**.

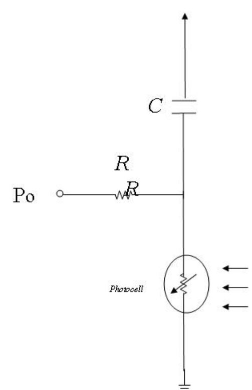

Fig. 8. Equivalent RC circuit.

A variation in the RC time will imply a variation of the incident light intensity. The RC circuit is connected with the BS2 trough a $220\ \Omega$ resistance, in order to prevent short circuit current to damage the basic stamp.

The multi-vehicle sensing platform can be remotely controlled by an external signal, capable to choice the functional mode, and to start and stop the simulation.

V. Bill of the material and prototype cost

The following is a table listing the parts cost and the prototype sum total.

Parts Name	Unit Cost	Quantity	Total
Boe-Bot Robot Kit	159.95	3	479.85
912MHz RF Transceivers	49.95	3	149.85
3 Function Universal Remote	10.00	1	10.00
Miscellaneous	70.00	1	70.00
		Total cost for the prototype	739.70

The three robots are essentially the same. The kit comes with the chassis, wheels, servos, and microcontroller. Various other parts are included, such as wires, resistors, capacitors, sensors. This is one of the reasons each package is so costly. The RF transceivers are sold separately. The remote will be used to start and stop the system. Miscellaneous costs comprises of shipping/handling charges, various other parts; light source, extension cables.

A. *Mass production cost analysis*

The prototyped system is a proof of concept and such will not be the final end product that will be mass produced. The end product is determined by the specific use of the system, which is formation control. If the application were to be underwater, additional costs of water proofing and propulsion needs to be considered, as well as a means to communicate with the surface operator. For UGV the issue will be the terrain the system will be made to operate in. Various forms of locomotion need to be looked into. However, mass production of the prototype variants for educational use, costs of an individual unit will be substantially less that the entire system. The parts needed for

Parts List	Unit Price	1 **unit**	5 **unit**	10 **unit**
Robot Chasis	1	23.50	117.50	235.00
Continuos rotation Servos	2	25.90	64.75	129.50
Basic Stamp 2 OEM	1	30.90	147.00	278.60
912MHz RF Transceiver	1	49.95	249.75	399.60
Light Sensor	1	5.95	29.75	59.50
Wheel, Wires, nuts, bolts		10.00	50.00	100.00
	total	1 **units**	146.25	
		2 **units**	731.25	
		3 **units**	1,462.50	
		bulk savings	72.50	260.30

As we can see the prototype model is substantially more costly than the massed produced units. The parts of the massed produced model will be largely unassembled since it is meant for educational use; assembly will be left to the students. The formation controls code for the microcontroller can either be created by the student or provided. This basic model does not contain any other sensors; if other applications were to be introduced into the system it would be a choice for the students to make. The system of formation controls is based on having multiple agents, and such bulk purchases are recommended.

VI. Conclusions and future works

The multi-vehicles sensing platform demonstrate some advantage as easy hardware and software implementation, good reliability working in emergency mode. The system shown good performances also with open loop control design. Anyway it is reasonable to think to improve the design through a closed loop control. To realize a closed loop controller, for example a proportional controller, we need a inertial platform in order to evaluate the actual state of the vehicle. Otherwise should be sufficient an ultrasonic sensor that is capable to evaluate relative distance between two vehicles, and correct the angular velocity of the servomotors trying to maintain the correct relative position.

VII. Appendix: PBasic codes

In attachment we have the programs used to command each of the three vehicles. The command lines are opportunely commented.