Potential Function Based Formation Control of Mobile Multiple-Agent Systems

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***Abstract*—In recent years, a great deal of interest has been focused on the control of mobile multi-robot systems. The primary reason for this interest in mobile multi-robot systems within the robotics research community is that such systems hold several advantages over single-robot systems. For example, these systems have the capability to quickly explore a large area, and for transporting heavy objects which may exceed the capacity of a single robot. One method of accomplishing these and other tasks is by controlling the formation of the system. In the research reported in this paper, the formation of a group of differential drive robots was controlled using a potential field strategy. Control methods were designed incorporating potential functions, and the results were validated in a physical arena. A group of three Khepera-II mobile robots was deployed using an OptiTrack motion tracking system, and experiments were successfully conducted to transport a box along the length of an arena, and to change the formation to avoid obstacles while maintaining group cohesiveness.**

Keywords – multi-robot systems; mobile agents; potential function control; vision sensing; distributed control; formation control; cooperative robotics

I. Introduction

Multi-robot research [1]–[9] is based on the principle of having a collection of robots accomplishing a desired task, rather than simply employing a single agent. For example, instead of having a large, single robot move a bulky object, one could use multiple robots or a swarm [10]–[17] to move it more effectively. An advantage of multi-agent systems [18]–[21] is that they offer better dexterity through more controllable components. Additionally, the effects of failure are minimized since multiple agents work together to accomplish the same task. Unlike a single agent system, one robot's failure is not crucial to task accomplishment since there may be several others agents cooperating [22] to complete the same task. Whereas fixed-base industrial robots [23], [24] have been used in dull, dirty, and dangerous environments, swarm robotics offers an even greater variety of applications that range from services to life saving operations. In addition, commercial applications include autonomous robots that move goods across warehouse distribution centers [25], detect embedded mines [26], and perform surveillance tasks [27], [28]. Fig. 1 shows the use of a swarm of ground robots

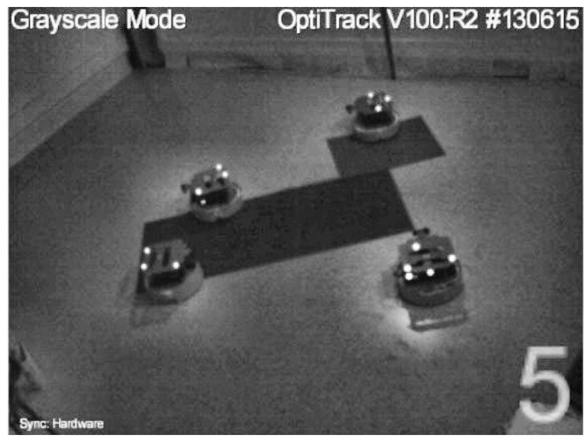

Fig. 1. Swarming robots carrying out a perimeter surveillance task. [29]

to carry out a perimeter surveillance task [29]. Aggregation and segregation of heterogeneous multiple agents [30]–[32] has also been recently researched.

Multi-robot control, however, may pose crucial issues due to an increased number of agents and slow computing capabilities. Inter-agent communication can be complex, especially when communication is not centralized or involves heterogeneous robot configurations [33]. Swarm robots [34] that are frequently small and depend on batteries as their power source have relatively low processing power and memory, restricting their abilities. Coordination and multi-agent formation [35] is also a challenge, as robust systems need to accommodate the addition, withdrawal, or failure of robots. Research in multi-robot systems has heavily drawn on the group behavior of biological systems [36] such as ants, fish, and birds to inspire coordination and formation strategies.

A major distinction in multi-agent systems can be found in centralized versus decentralized control [37], [38]. Centralized control entails communication and direction to come from a centralized controller, whereas decentralized control implies that each robot is independently controlled. Centralized control has the benefit of being able to monitor the entire system. Since processing is done off board, less processing equipment is required onboard and the cost of the agents is decreased. However, the performance of centralized control is hindered by high communication requirements and limited processing power. The number of agents the system can accommodate is finite as it is restricted to the controller's hardware limitations. Unlike centralized systems where the entire system can fail should the central controller fail, each robot has the sensors and actuators to independently assert control over itself in decentralized systems. Consequently, a single agent's failure does not create an adverse effect across the entire system. A large number of robots can be used since the number of agents is not limited by the capabilities of the central controller. Trade-offs are made as independent processing results in increased costs and complexity.

The primary goal of this research was to demonstrate the effectiveness of formation control via potential fields in a physical arena. Formation control offers many useful applications to swarms of mobile robots as it allows a group of robots to carry out certain tasks more effectively than a single robot. In [39] a group of three truck-like robots transport a large box by moving them in a strict formation. In [40] formation control allows a group of robots to perform minesweeping and scouting tasks.

The research effort emphasized the control of a swarm of robots to create formations, navigate, and change formation. The use of potential fields [41] allowed individual Khepera-II robots to achieve their goal positions while avoiding other robots with simple calculations carried out on a central computer. The controller required position and orientation information of each robot, which was provided by a vision system consisting of three infrared cameras. Communications were sent wirelessly between the central computer and each robot using radio communication turrets mounted on the robots and a radio base unit connected to the computer. Several formation maneuvers were carried out to test the functionality of the controller and the experimental setup. Successful completion of the tests demonstrated the capability of the potential field-based controller.

II. EXPERIMENTAL SETUP

The experimental setup consisted of a planar rectangular test table, an OptiTrack vision sensing system [42], three mobile Khepera-II differential drive robots [43], and a 64-bit Windows 7 personal desktop computer. Details of these items are given below.

A. Mobile Robots

The mobile robots used were K-Team Khepera-II differential drive robots. These robots use a DC motor to move each of the two wheels. An on-board motor controller can control the speed or position of each motor. Speed commands sent to the motors range from a minimum linear speed of $8mm/s$ up to a maximum speed of $1m/s$.

The Khepera-II is configured to accept expansion turrets mounted on the top face of the robot. Options to mount on the robots range from grippers to communications turrets. In this research, each robot was equipped with a radio turret acquired from K-Team. Each radio turret has its own local processor used for managing the communication procedure, including data encoding, transmission and reception, and error detection and correction. Distinct ID numbers are set for each turret with a series of switches located on the top of the turret. The radio turrets allow for communication with other radio turret-equipped robots as well as the radio base at a rate of $9600baud$. The radio base from K-Team was also used in this research. The radio base, which has its own local processor for managing the communication procedure, was connected to the central computer through an RS232 serial port. A single radio base unit can communicate with up to 31 radio turrets, sending broadcast or directed messages. A Khepera-II robot equipped with a radio turret, and the radio base, are shown in Fig. 2.

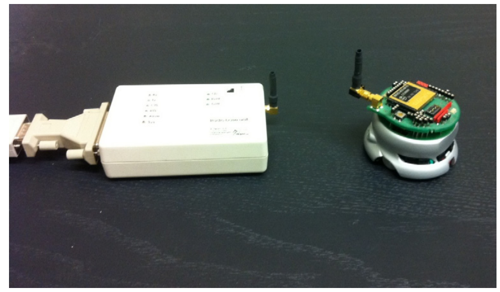

Fig. 2. Radio base and a radio turret mounted Khepera-II robot.

B. Test Arena

The test arena used was a $1.63m \times 0.86m$ wooden platform with $8cm$ high walls. The base was painted black to avoid reflection from overhead lights.

C. Vision System

Calculating the potential field at each time step requires position and orientation information for each robot and position information for each obstacle. To achieve this objective, a system of three NaturalPoint OptiTrack Flex V100:R2 cameras were used. Using the TrackingTools (TT) version 2.3.1 software from NaturalPoint, the cameras are able to track user-defined rigid bodies in 3-D space composed of reflective markers. The markers reflect infrared light emitted by the cameras, which is then detected by the cameras. In order to track each robot, the robots were fitted with black cardboard plates with unique patterns of reflective markers. Fig. 3 shows three robots fitted with their distinct ID markers and the 3-D model of the markers in TrackingTools. A set of markers can be identified as a trackable rigid body, and the software generates position and orientation information in the 3-D space.

The tracking data from TrackingTools running on the central computer was sent to MATLAB on the same computer via VRPN streaming [44]. A MEX file was created to

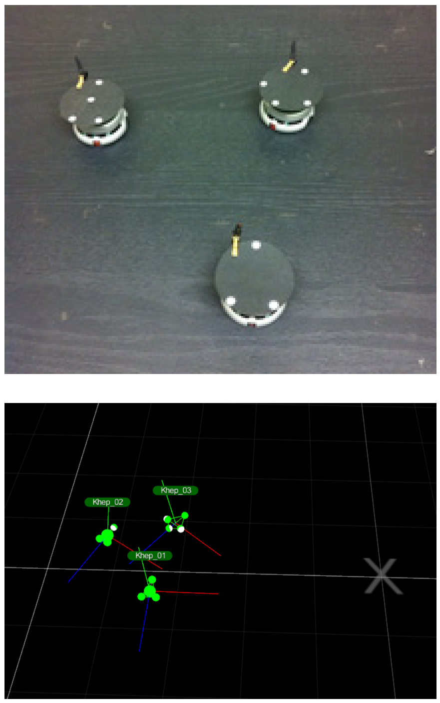

Fig. 3. The reflective marker mounted robots and TrackingTools software generated position and orientation information.

call the tracking data from TrackingTools in MATLAB. The cameras were connected with USB cables to a NaturalPoint OptiHub, which was connected to the central computer via a USB cable. An aluminum truss structure was constructed above the test arena to enable the cameras to have a full view of the entire arena, with all cameras mounted on a single bar running the length of the truss.

III. CONTROLLER DESIGN

A. Artificial Potential Field

Potential field methods of robot control offer a simple yet powerful means of controlling navigation and obstacle avoidance [45] for single or multi-agent systems. Defining an artificial potential field over the entire arena with potential energy minima at goal positions creates forces that attract each robot to their goals while repulsing each robot away from obstacles. An overview of potential functions is given in [46].

If $\mathbf{q} = [x, y]^T$ is defined as the position of the robot in the two dimensional workspace, the attractive potential is defined as:

$$U_{att}(\mathbf{q}) = \frac{\epsilon}{2}\rho^2(\mathbf{q}, \mathbf{q}_{goal}) \tag{1}$$

where ϵ is a positive coefficient, $\rho(\mathbf{q}, \mathbf{q}_{goal}) = ||\mathbf{q}_{goal} - \mathbf{q}||_2$ is defined the scalar distance between the robot's position and the goal position. The force, which is equal to the negative gradient of the potential, is therefore:

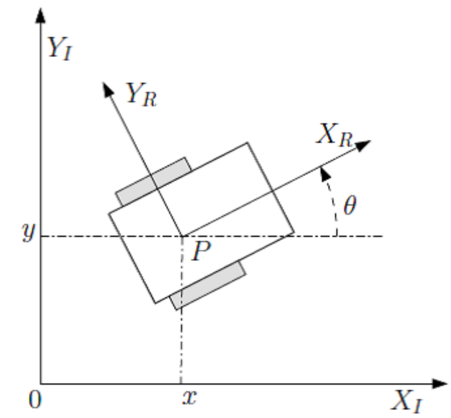

Fig. 4. Differential drive robot in planar coordinate frame [47].

$$\mathbf{F}_{att}(\mathbf{q}) = -\nabla U_{att}(\mathbf{q}) = \epsilon(\mathbf{q}_{goal} - \mathbf{q}) \tag{2}$$

Similarly, the avoidance potential function is defined as:

$$U_{rep}(\mathbf{q}) = \begin{cases} \frac{\eta}{2}\left(\frac{1}{\rho(\mathbf{q}, \mathbf{q}_{obs})} - \frac{1}{\rho_0}\right)^2, & \text{if } \rho(\mathbf{q}, \mathbf{q}_{obs}) \leq \rho_0 \\ 0, & \text{if } \rho(\mathbf{q}, \mathbf{q}_{obs}) > \rho_0 \end{cases} \tag{3}$$

where η is a positive coefficient and ρ_0 is the user-defined maximum distance from the robot to the obstacle in which the repulsive force is felt. Since $\mathbf{F}_{rep}(\mathbf{q}) = -\nabla U_{rep}(\mathbf{q})$, the repulsive force is given by:

$$\mathbf{F}_{rep}(\mathbf{q}) = \begin{cases} \eta\left(\frac{1}{\rho(\mathbf{q}, \mathbf{q}_{obs})} - \frac{1}{\rho_0}\right)^2 \frac{\mathbf{q_{obs}} - \mathbf{q}}{\rho^2(\mathbf{q}, \mathbf{q}_{obs})}, & \text{if } \rho(\mathbf{q}, \mathbf{q}_{obs}) \leq \rho_0 \\ 0, & \text{if } \rho(\mathbf{q}, \mathbf{q}_{obs}) > \rho_0 \end{cases} \tag{4}$$

The total force acting on robot i for a system of n robots is the algebraic sum of the attractive force from the goal position and the repulsive forces from the n obstacles, given by:

$$\mathbf{F}_{total,i} = \mathbf{F}_{goal,i} + \sum_{m=1}^{n} \mathbf{F}_{rep,m} \tag{5}$$

The resulting total force is a two-dimensional vector in the plane of the arena.

B. Robot Kinematics

Converting the total force acting on a robot at each time step into navigation commands requires examination of the kinematic model of the robot. A concise overview of the kinematic equations of differential drive robots can be found in [47]. Fig. 4 schematically illustrates a differential drive robot in a two-dimensional coordinate system.

The motion of the robot can be described by:

$$\dot{x} = u\cos\theta - v\sin\theta \quad (6)$$

$$\dot{y} = u\sin\theta + v\cos\theta \quad (7)$$

$$\dot{\theta} = \omega \quad (8)$$

where u is the linear velocity of the robot in the x-direction in its reference frame, v is the linear velocity of the robot in the y-direction in its reference frame, and ω is the angular velocity of the robot about the z-axis in its reference frame. For a differential drive robot, the motion can be described by:

$$u = \frac{(\omega_R r + \omega_L r)}{2} \quad (9)$$

$$\omega = \frac{(\omega_R r - \omega_L r)}{l} \quad (10)$$

where ω_R is the angular velocity of the right wheel, ω_L is the angular velocity of the left wheel, r is the radius of each wheel, and l is the wheel base of the robot. Through simple linear algebra, the required wheel angular velocities can be expressed by:

$$\omega_R = \frac{u}{r} + \frac{\omega l}{2r} \quad (11)$$

$$\omega_L = \frac{u}{r} - \frac{\omega l}{2r} \quad (12)$$

C. Connecting Potential Fields to Kinematics

A simple and reliable first-order controller was implemented. The error angle, θ_{err}, is defined as the angle between the direction of the total force vector and the orientation of the robot. The desired angular velocity was then controlled proportionally to this error signal; i.e., $\omega_{des} = K_\omega \theta_{err}$.

The desired linear velocity, u_{des}, of the robot is set to be proportional to the magnitude of the total force vector multiplied by the cosine of θ_{err}. With ω_{des} and u_{des}, the required wheel angular velocities can be easily calculated from (11) and (12). Formations can be controlled by using the previous methods to set target positions for each robot at certain points of a formation. By defining one robot as the leader [48] with certain target positions and the other robots as followers with target positions in relation to the leader's position, the artificial potential field will drive the robots into formation.

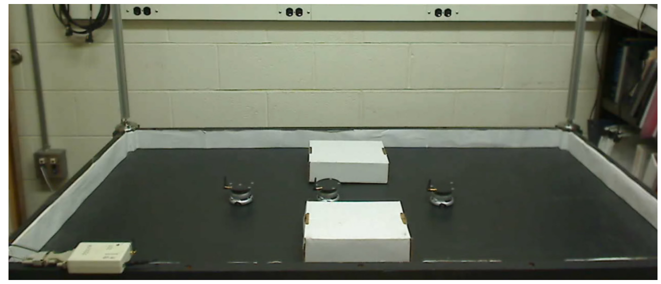

Fig. 5. The robots formed a line formation to pass through a tunnel.

D. Controller Code

The controller code was written in MATLAB 32-bit R2010b. The structure of each controller was a discrete-time loop in which tracking information was retrieved from the TrackingTools VRPN stream; forces from the potential field were calculated for each robot; desired wheel speeds were calculated for each robot; commands were sent through the radio base to each robot; and plots were generated.

In order to solve an inherent communications issue, a 500 ms time pause was introduced at the start of the control loop. The maximum allowed linear velocity of the robots was decreased to compensate for the increased time step. This technique led to successful tests and fairly reliable communications. This approach did have a drawback however, since it meant that the robots had to move slower. With this pause, the controller loop generally took 1 second to complete one iteration.

E. Central Computer

The central computer used to run MATLAB and TrackingTools was a Windows 7 64-bit PC with a quad-core, 3.00GHz processor and 8 GB of RAM.

IV. EXPERIMENTAL VALIDATION

A. Pyramid to Line Formation Change

In the first test, it was desired to have a group of three Khepera-II robots to start from random initial positions, form a triangle, switch to a line formation, travel through a tunnel-like obstacle in a line formation, and then re-form a triangle once the tunnel had been cleared. Three trials were carried out for this experiment, and in all trials the robots were successfully able to complete the maneuvers without collisions. Fig. 5 shows a picture of the robots taken during the formation procedure.

Fig. 6 shows plots for the position of the robots. From approximately 0 to 12 seconds, the robots were forming the first triangle from their random starting points. From 12 to 23 seconds, the robots moved to form a straight line. From 23 to 47 seconds, the robots were traveling across the table in a straight line. The robots moved to form the second triangle during the remainder of the test.

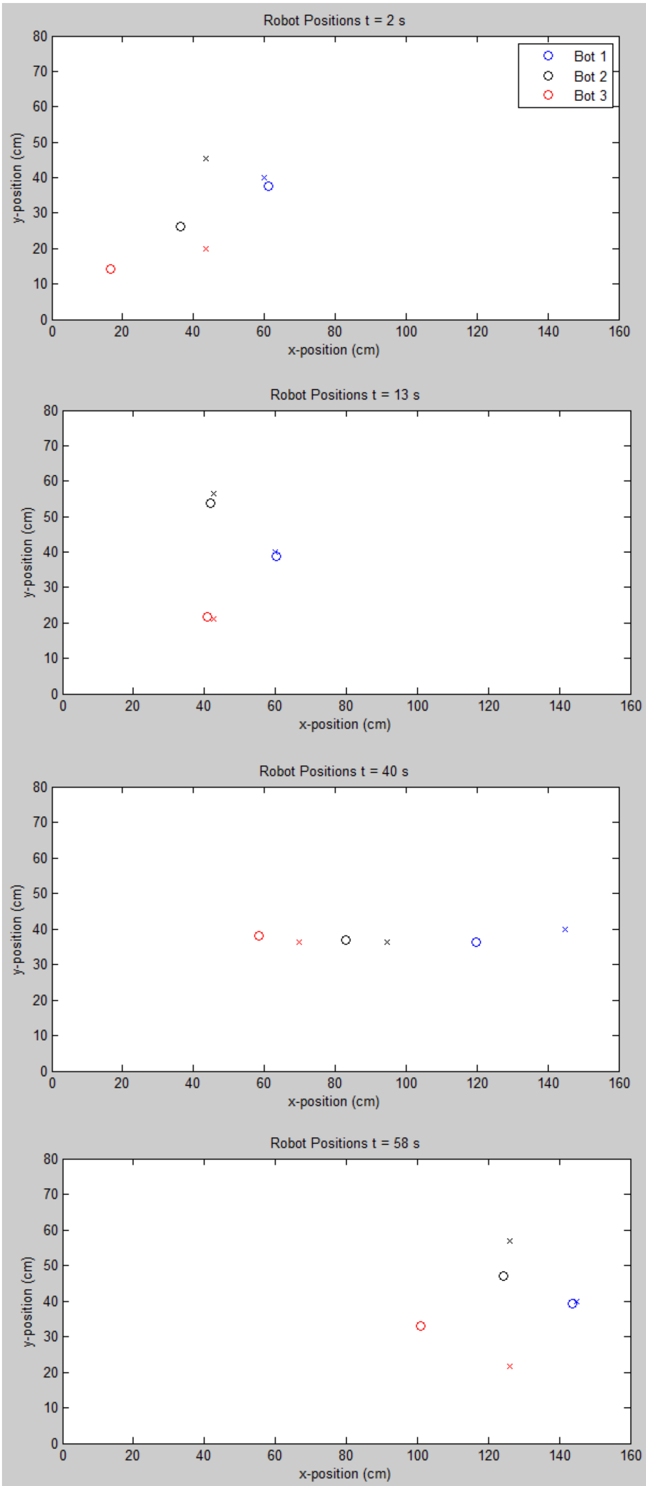

Fig. 6. Plots of the robot position during the formation change test.

B. Box Push Test

The second test involved using three robots to move a light cardboard box across the arena. The lead robot traveled in front of the box and served only to guide the follower robots. The two follower robots pushed on the backside of the box. Multiple trials were carried out, and in each trial the robots were able to transport the box most of the way across the arena. However, the motion was not smooth and the box often shifted to undesirable positions. This was due to the slow response time of the robots caused by the necessary pause in the control loop. Nevertheless, the test proved that the concept was feasible using the experimental setup. Modification of the controller could likely lead to a smoother transportation of the box. Fig. 7 shows an image of the box during its transportation.

Fig. 7. The Khepera-II robots transporting a cardboard box across the arena.

V. CONCLUSION

This research demonstrated the ability of simple potential field functions to control the formations and cooperative movements of mobile robots on a physical test bed. Several tests verified the validity of the controller and its usefulness with Khepera-II mobile robots. Although communication was limited by the hardware and reduced the functionality of the controller, compromises were made to allow the system to function and complete the required tasks. Future research in this area would include optimizing the response time of the system while maintaining successful communication over the radio turrets. In addition, the validation of the controller opens the door to different tests with formation control. Optimizing the response time of the system using more efficient and reliable sensors [49] could permit the successful introduction of more robots. Videos of the experiments conducted are available on the internet at http://www.youtube.com/user/DukeRAMALab

VI. ACKNOWLEDGMENT

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