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Vector Field Based Formation Control of Multi-Robot System

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Abstract: Multi-robot system as formation can perform better than a single robot in many situations like collective movement of objects, search and rescue operations etc. In this paper a vector field framework is used for achieving path planning for a single robot, and a nonlinear controller is designed for tracking this path. The tracking controller is later extended for achieving formation control of multi-robot system. Asymptotic stability of the controller for any reference path is ensured by using Lyapunov theory. The robots may encounter obstacles in their path during tracking or may collide with each other during the switching of formation patterns. Obstacle avoidance and collision avoidance have been achieved by modified vector field. If the terrain is constrained then it needs to switch from one formation to another according to the terrain requirements. Thus the capability of switching of formation or reconfiguration is an important aspect in the control of multiple mobile robots. If one of the member robots is lost, then the other robots continue with the remaining formation structure and thus ensures robustness against loss of team member. From the extensive simulations using Matlab environment it is seen that any formation of mobile robots is achieved in addition to reconfiguration and obstacle avoidance. The formation control algorithm has been experimentally demonstrated by a series of experiments conducted using LEGO NXT Mindstorm robot kit.

Keywords: Nonlinear control, Formation control, vector field, Obstacle avoidance, Reconfiguration, LEGO NXT Mindstorm, RWTH, Bluetooth.

1. INTRODUCTION

Multi-robot formation control is an active research topic because of its use in various applications such as surveillance, automatic control, commercial cleaning, robot navigation, material handling etc. and also due to its ability to work in hazardous environment where human can't reach. The term formation control can be interpreted as the process of coordination of multiple robots to get into and to retain a formation of particular shape.

The major inspirations of researchers to this formation control problem are as follows from Arai et.al (2002).

(a) Need of multi-robot systems: A given task may be too complex or cannot be physically executable by a single robot at all, means multiple robots can achieve the same task reducing execution time and improving performance.

(b) Biological inspirations: Group-level behaviours such as schooling and flocking are exhibited as emergent properties from individual-level behaviours. (c) Challenging control problems: A wheeled mobile robot is an under actuated system having degrees of freedom less than the number of actuators. The formation control problem for under actuated system is challenging because it exhibit nonholonomic constraints and most of them are not fully feedback linearizable. Also, decentralized controller design for multi-robot systems face lot of challenges not present in centralized or single robot systems. The challenging control problems also include complex interactions, inherent parallelism, uncertainties, incomplete information, high system dimensionality etc. Navarro et.al (2013) explains many applications in which multi-robot formations can perform better than a single robot system to prove the significance of multi-robot formation control.

Vector field path following for small unmanned air vehicles is proposed by Nelson et.al (2007). From this idea, Kwon et.al (2009) calculated vector field around the route of the leader to be followed for wheeled mobile robot. Without considering obstacle avoidance, Chwa et.al (2012) proposed hierarchical formation which is a combination of line and column formations. Obstacle avoidance in formation is dealt by Yu-Cheng et.al (2007).

In this paper an attempt is made to develop a formation control algorithm for a multi- robot system based on vector field incorporating obstacle avoidance algorithm also. Path planning for the robots is done using vector field method and then a nonlinear controller for target tracking is designed. This controller is extended for formation control by using the following concept: Reference path with reference to the target is derived for each member robot in the formation using column formation, row formation

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or a combination of column and row formations. When each robot follows its own desired path, the formation is automatically achieved. A modified vector field approach is proposed for obstacle avoidance when the robot encounters an obstacle in its path. If the terrain is constrained then the formation need to switch from one formation to another according to the terrain requirements. It is also simulated. Another objective is to ensure robustness of the system against the loss in team population.
This paper is organized as follows. Generation of reference trajectory and modelling of the system is described in section 2. Vector field generation for path planning is discussed in section 3. In section 4, controller for formation control is proposed. In section 5, formation control algorithm is discussed. Section 6 deals with obstacle avoidance. Simulations carried out are demonstrated in section 7. In section 8 experimental results have been discussed. Paper is concluded in section 9.

2. GENERATION OF REFERENCE TRAJECTORY AND SYSTEM MODELLING

In this paper the reference trajectory is generated by a virtual target robot and the follower robots follow this virtual target as a formation. Here, virtual target and the follower robots are modelled as wheeled mobile robots of unicycle type. In this work kinematic model based controllers are used. The kinematics of the i^{th} robot is described by the following equations:

$$\dot{x}_i = v_i cos\theta_i \quad (1)$$

$$\dot{y}_i = v_i sin\theta_i \quad (2)$$

$$\dot{\theta}_i = \omega_i \quad (3)$$

where x_i and y_i are position coordinates, θ_i is the orientation angle of the robot from the horizontal axis, v_i and ω_i are the linear and angular velocities respectively. Subscript i will be equal to t in the case of the virtual target and equal to c_1, c_2 etc. for the follower robots respectively. By suitably providing v_t and ω_t for this virtual target, different reference paths are generated. v_c and ω_c are the control signals to be provided by the controller.

3. PATH PLANNING

Path planning of the mobile robot is done using vector field method. In this method, the vector field around the path to be tracked is calculated. The vectors (arrows) in the field are directed towards the path of the leader to be followed and represent the desired orientation of the follower robot. In Fig.1, the circle represents the track of the target, and the arrows represent the vector fields generated from the track. A straight line trajectory is a special case of circle with an infinite radius and thus vector field can be generated for any track. $v_t > 0$ represents that the target is moving forward. $\omega_t > 0$ represents anticlockwise rotation. As can be seen in Fig.1, the mobile robot can follow the target, when it moves along the direction of the vector field. Fig. 2 shows the vector field geometry for trajectory tracking between the target and the follower robot. Centre Of Rotation (COR (x_{cr}, y_{cr})) is the centre of the circular track of the target. Here γ is the angular position with respect to the COR. The COR can be calculated as (Kwon et.al (2009)).

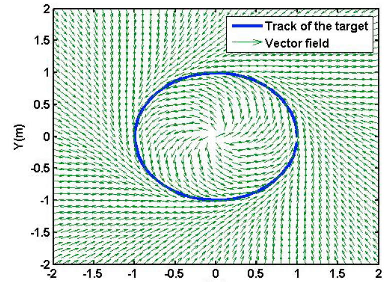

Fig. 1. Vector field generated for a circular track for $v_t > 0$ and $\omega_t > 0$.

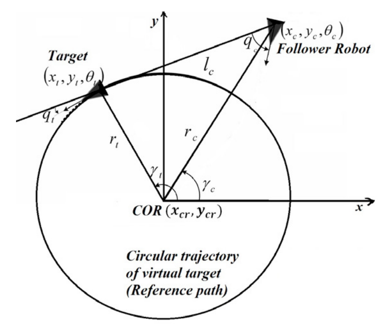

Fig. 2. Vector field geometry for trajectory tracking.

$$x_{cr} = x_t + r_t cos(\theta_t + sgn(\omega_t)sgn(v_t)\pi/2) \quad (4)$$

$$y_{cr} = y_t + r_t sin(\theta_t + sgn(\omega_t)sgn(v_t)\pi/2) \quad (5)$$

The vector field is generated as (Chwa et.al (2012)).

$$\theta_d(e_r) = \gamma_c + \frac{\pi}{2}sgn(\omega_t) + sgn(\omega_t)tan^{-1}(e_r) \quad (6)$$

when $v_t \geq 0$ and

$$\theta_d(e_r) = \gamma_c + \frac{\pi}{2}sgn(\omega_t) + sgn(\omega_t)tan^{-1}(e_r) - \pi \quad (7)$$

when $v_t < 0$. where, $e_r = r_c - r_t$.

4. CONTROLLER DESIGN

A nonlinear controller for target tracking is designed based on the vector field such that the follower robot tracks the target with minimum error. In Fig. 2, l_c is the distance between the target and the follower robot. Differentiating θ_d we have,

$$\dot{\theta}_d = \frac{v_c}{r_c}\sin(\theta_c - \gamma_c) + \mathrm{sgn}(\omega_t)\frac{v_c \cos(\theta_c - \gamma_c)}{1 + e_r^2} \quad (8)$$

Choose tracking errors as

$$e_l = l_c, \;\; e_\theta = \theta_c - \theta_d, \;\; e_r = r_c - r_t \quad (9)$$

A nonlinear controller is synthesized so that the tracking errors in (9) asymptotically converges to zero. We have,

$$\dot{e}_l = v_t cos(q_t) - v_c cos(q_c) \quad (10)$$

$$\dot{e}_\theta = \omega_c - \frac{v_c}{r_c}\sin(\theta_c - \gamma_c) - \mathrm{sgn}(\omega_t)\frac{v_c \cos(\theta_c - \gamma_c)}{1 + e_r^2} \quad (11)$$

v_c and ω_c are chosen such that the derivatives of Lyapunov candidate functions V_1 and V_2 are negative definite (equations (18) and (22)). We can derive the target tracking control laws as