Applied Computer Science, vol. 17, no. 3, pp. 60–72
doi: 10.23743/acs-2021-21

Submitted: 2021-07-14 | Revised: 2021-09-07 | Accepted: 2021-09-21

Multi-Robot Systems, Formation control, Behavior-Based Control, Switching strategy, Stateflow

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BACKWARD MOTION PLANNING AND CONTROL OF MULTIPLE MOBILE ROBOTS MOVING IN TIGHTLY COUPLED FORMATIONS

Abstract

This work addresses the development of a distributed switching control strategy to drive the group of mobile robots in both backward and forward motion in a tightly coupled geometric pattern, as a solution for the deadlock situation that arises while navigating the unknown environment. A generalized closed-loop tracking controller considering the leader referenced model is used for the robots to remain in the formation while navigating the environment. A tracking controller using the simple geometric approach and the Instantaneous Centre of Radius (ICR), to drive the robot in the backward motion during deadlock situation is developed and presented. State-Based Modelling is used to model the behaviors/motion states of the proposed approach in MATLAB/STATEFLOW environment. Simulation studies are carried out to test the performance and error dynamics of the proposed approach combining the formation, navigation, and backward motion of the robots in all geometric patterns of formation, and the results are discussed.

1. INTRODUCTION

Motion planning and control of multiple mobile robots moving in tightly coupled formation garnered enormous research interest in the past two decades owing to the applications of such systems in security and surveillance, defense, disaster management, driverless vehicle platoons, and material handling in industrial manufacturing environments. The essential problem in such tightly coupled systems is to make the systems efficiently plan their paths by navigating the environment in a coordinated fashion avoiding the obstacles as well as each other to achieve its goal. Therefore, it refers to the problem of developing a closed-loop control strategy that controls the relative position and orientation between the group of robots during its fly (Werger & Mataric, 2001; Barfoot & Clark, 2004; Alonso-Mora, Baker & Rus, 2017; Kuppan Chetty, Singaperumal & Nagarajan 2011a, 2011b; Kuppan Chetty et al., 2011).

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As reported in various literature, numerous approaches, algorithms, topologies for motion planning and control of multiple robots in tightly coupled formation and its advantages, disadvantages, and applications are addressed in (Arkin, 1998; Dougherty et al., 2004; Li & Xiao, 2005; Mataric & Michaud, 2008; Kuppan Chetty et al., 2012; Xu et al., 2014; Lee & Chwa, 2018; Wang & Philips, 2018). Behavior-Based and Leader-Follower approaches are commonly used and widely accepted by researchers due to their simple and scalable nature (Soni & Hu, 2018; Wang & Philips, 2018). However, the major limitation is that the ability of the system remains in a stable formation in dynamically changing unknown environments filled with obstacles.

In most of the studies, found in the literature, the robots are made to move in the formation by specifying the trajectory of the leader robots and make the other robots efficiently track the assigned leader without perturbing the formation throughout the fly (Li & Xiao, 2005; Kuppan Chetty, Singaperumal & Nagarajan 2011a, 2011b; Kuppan Chetty et al., 2011, 2012). Though, when it comes to guiding the robots in the unknown environment, apart from tightly coupled formation, the robots also need to plan their paths to reach their particular goal by avoiding collision between themselves and obstacles in the environment of interest. Under such conditions, as the number of robots increases in the group, the control methods reported in the literature fails due to their centralization and requirement of higher communication bandwidth (Li & Xiao, 2005; Kuppan Chetty et al., 2011; Soni & Hu, 2018; Wang & Philips, 2018). Further, it is difficult to design and model the system in a traditional manner. Therefore, it needs a distributed controller that combines formation planning along with the navigational capabilities of the group of robots in achieving a stable formation with wide communication capabilities between the group members to have knowledge about their states and the actions of their teammates.

One such control strategy is addressed and employed in (Kuppan Chetty et al., 2011, 2012), where a hybrid control approach combining the advantages of behavior-based and leader-follower approach is used to control the group of mobile robots in tightly coupled formation by planning its path, avoiding an obstacle in the dynamic unknown environments. In this approach to achieve the desired objective of the formation planning and navigation in a distributed manner, the total functionality of the multi-robot system is decomposed into functional behaviors such as Navigation and Formation, based on the motion states of the robots utilizing the methodology of the behavior-based reactive approach. The formation amongst the robot is achieved by a tracking controller using the leader-follower approach and the navigation and motion planning by using the heuristic controllers coupled in the layered manner as suggested in (Arkin, 1998; Mataric,2008). The important aspect of controlling multiple robots in the formation is the active obstacle avoidance on the follower robots, which is very crucial for the robots to remain in the closed defined geometric pattern through the exchange of leaderships between the robots is also addressed in (Kuppan Chetty et al., 2011, 2012).

Even though the robots are able to move in a closed defined formation along with navigational and obstacle avoidance on both leader and follower robots by exchanging the leaderships, there exists a deadlock situation when all the robots experience obstacles on their path at the same time. This deadlock situation arises as a result of the confusion in lending their leadership to one of the robots in the group. One possible solution, in this case, is to make all the robots plan their motion in the backward direction without changing their orientation to a safer distance and continue to plan its path afterwards. However, in most of the studies reported in the literature, the tracking controller is designed only to track the leader robot moving in the forward direction using the kinematics of the robots. Therefore, addressing this deadlock situation and backward motion is critically important amongst the group of robots moving in a tightly coupled formation navigating unknown environments.

The organization of the manuscript is as follows. Literature on the backward motion control of multiple mobile robots, its limitations, and the need for a distributed switching control strategy to address the deadlock situation is described in section 2. The detailed description and methodology on the design of switching control strategy and theoretical formulation for backward motion controller are presented in section 3. Section 4 deals with the modeling and simulation studies in MATLAB/STATEFLOW environment. The simulation results that are obtained to validate the performance of the proposed approach are discussed in detail in section 5. Finally, the outcome of this work is concluded and the scope for further improvements is presented in section 6.

2. RELATED WORK

In recent times, the backward motion control of robots moving in a tightly coupled formation garnered enormous research interest amongst researchers. Autonomous backward navigation of mobile robots using remembered landmarks is addressed in (Petukhov & Rachkov, 2009). The reference points along the trajectory are used to design the control algorithm for the control of robot motion. This method maintains tight coupling between the robot and makes an alternative decision commanding the robot in backward motion for some distance to avoid an obstacle in its path. However, the major drawback of this method is the complex computational algorithm used to compute the reference points and coordinating the backward motion of the robots is only for a minimum distance in real-time.

A nonlinear smooth feedback tracking control law using the line- of sight method and PID algorithm for the mobile robot group tracking a rectilinear path in the backward motion in an in inline formation is proposed and addressed in (Ma et al., 2014; Cheng et al., 2017). Similarly, motion control of n passive trailers off-hooked with the mobile robot in backward motion is addressed in (Chung et al., 2011; Petrov, 2010).

Here leader robot is considered as a truck and the follower robots as the trailer in in-line formation with the separation distance between them is considered a hooked distance. The trajectory-based tracking control algorithm is addressed where the trailers trajectory is computed using the set of equations using the kinematic model of the robots and trailer considering the off hooked distance and the steering angle as the parameters in leader – referenced model. Although the results show the efficient control of robots in backward motions, the main disadvantage is that the presence of a set of non-linear equations in the tracking controller and linearizing the models to obtain the reference trajectory makes the system complex to understand and increases the computational cost as well as hinders the performance of the system. The major disadvantage is this system works only during the backward motion.

In the approaches that have been devised in the literature for the backward motion of the mobile robots, the backward motion control problem is formulated as a trajectory-following problem, rather than as the control of independent, generalized coordinates. The motion control is complicated because the kinematic model is represented by highly nonlinear equations.

The reversing of robots is an open-loop unstable control problem. In addition, the robots must incorporate the navigation capabilities along with the two major important aspects of alignment and synchronization while positioning the robots in the tightly couple formation moving in the backward direction are to be considered. Therefore, it is necessary to develop a distributed control strategy able to drive the robots in both the backward and forward motion during navigation in tightly coupled geometric patterns for achieving a stable formation during its fly.

Inspired from the observations from the literature, a distributed switching control strategy in behavior-based approaches, like the one addressed in (Alonso-Mora, Baker & Rus, 2017; Kuppan Chetty et al., 2011; Dougherty et al., 2004) is developed incorporating the backward motion control of robots is developed and presented in this work. A tracking controller addressed in (Kuppan Chetty et al., 2011; Dougherty et al., 2004) considering the leader referenced model is used for the robots to track its leader's path while navigating the environment. When a deadlock situation arises, the controller switches to the backward motion tracking controller where the robot motion control is developed using a simple geometric approach using the Instantaneous Centre of Radius (ICR) and differential drive kinematics of the robots. The proposed approach combines the formation planning, navigation, and obstacle avoidance of robots addressing the deadlock situations of driving the robots effectively in the backward motion without perturbing the formation of the robots. The performance and error dynamics of the proposed approach are investigated through simulation studies in MATLAB/STATEFLOW environment.

3. METHODOLOGY

In order to meet the collective objective of the robot group to efficiently navigate the environment along with a stable tightly coupled formation, a layered distributed control architecture, where the fundamental behaviors/motion states of the robots are considered as components is developed and presented in (Kuppan Chetty et al., 2011, 2012) as shown in Figure 1. In this layered design, the total functionality of the system is divided into a set of functional behaviors such as the lower-level navigation and higher-level formation, based on the motion states of the robots, using the methodology of the behavior-based reactive approach designed by (Arkin, 1998; Mataric, 2008). These two levels work on individual goals concurrently and asynchronously, where the entire sets of behaviors are swapped in and out of execution which yields the collective task upon integration, for achieving the goals such as navigation and formation. The behavior/motion states are selected by the robots based on the information perceived by the robot sensors explicitly and implicitly from the environment during the fly. More details on the realization of individual behaviors, assumptions used to formulate the behaviors, arbitration, and coordination techniques could be found in (Kuppan Chetty et al., 2011, 2012).

Considering the objective of driving the robots in the backward motion without losing the formation, the higher-level formation behavior is decomposed into two and arbitered using the priority-based arbitration technique as in the rest of the system as shown in Figure 1, which is the modified form from (Kuppan Chetty et al., 2011, 2012). The decomposed behaviors are the generalized tracking controller which uses the theoretical formulation of closed-loop feedback control technique using the kinematics of the robots and the geometric controller using the Instantaneous Centre of Curvature/Radius (ICC/ICR) based on the velocities of the robots, responsible for driving the robots in the backward motion. These controllers swap themselves in and out of execution based on the relative motion of their leader, to remain in the defined formation. In both cases, the kinematics of a non-holonomic differential drive robot is considered in the realization of the control law. The detailed formulation of the generalized tracking controller and the geometric controller is discussed in the subsequent sections.

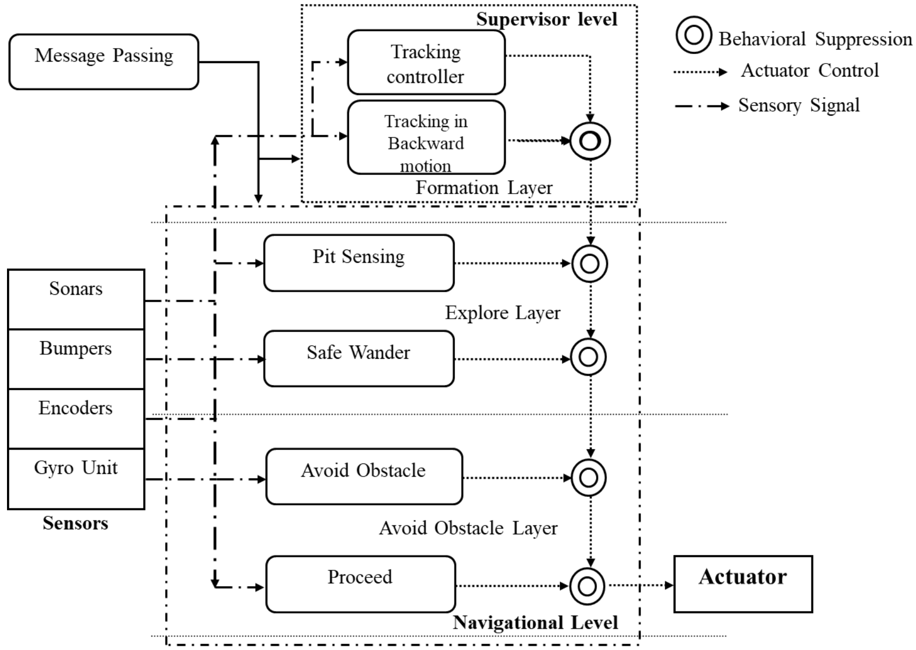


Fig. 1. Behavior-Based Switching Control Architecture for Multi-Robot Formation with modified formation layer

3.1. Generalized Tracking Controller

The generalized tracking controller used to position the robot in the tightly coupled formation is modeled based on the kinematics of the non-holonomic wheeled mobile robot in Figure 2. Let R_1 be the robot designated as leader and R_2 be the robot designated as a follower in which the direction of motion represents the *x*-axis, the robot frame. The robot R_2 is made to follow the leader R_1 in any geometric pattern such as inline, collateral, and parallel as illustrated in Figure 2. The posture of the robots in the group is given by x_L, y_L,θ_L and x_{Fi}, y_{Fi},θ_{Fi} where L and F represent the leader and follower, respectively. Let l_d be the desired linear separation and φ_d be the desired angular separation. it is necessary to maintain the desired linear and angular separation between the robots to remain in the tightly coupled formation. The translational and rotational velocities of the leader and follower robots are υ_L, ω_L and υ_F, ω_F respectively. The closed-loop tracking controller is designed such that the follower robots estimate their wheel velocities in a way that the formation/separation errors (linear and angular) reduce asymptotically to zero and position themselves in the desired geometric pattern with its leader as shown in Figure 3. Here the control problem reduces to a trajectory tracking control problem rather than the regulation problem of the follower by observing the leader's information.

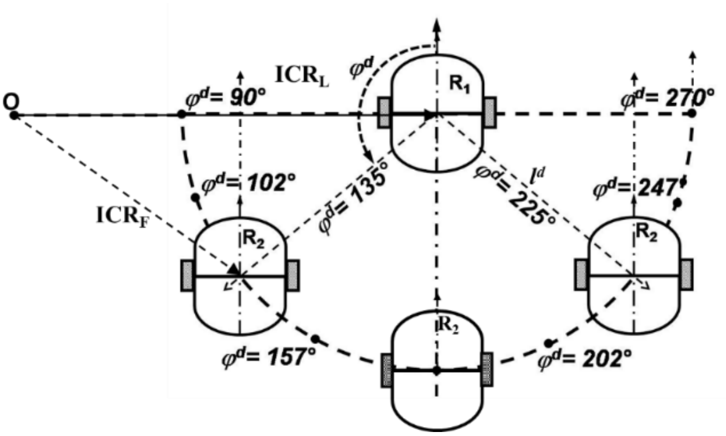


Fig. 2. Position of Robots in desired linear and angular separation describing the formation topologies

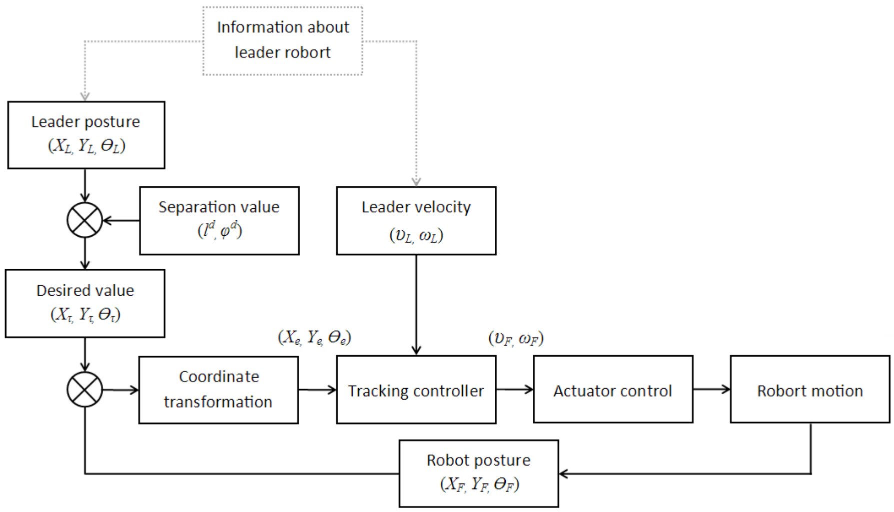


Fig. 3. Generalized tracking controller illustrated in (Kuppan Chetty, et al., 2011, 2012)

The details of the formulation of the trajectory tracking controller could be observed in (Kuppan Chetty et al., 2011, 2012). Hence, based on the kinematic model, the position of the robots and error coordinates in the robot frame and feedback linearization as given in (Kuppan Chetty et. al., 2012), the tracking control law for estimating the velocities υ_F and ω_F of the follower robots is obtained as:

$$\begin{bmatrix} v_F \\ \omega_F \end{bmatrix} = \begin{bmatrix} \cos\theta_e & l^d \sin(\varphi^d + \theta_e) \\ \frac{\sin\theta_e}{h} & \frac{l^d \cos(\varphi^d + \theta_e)}{h} \end{bmatrix} \begin{bmatrix} v_L \\ \omega_L \end{bmatrix} + \begin{bmatrix} k_1 & 0 \\ 0 & \frac{-k_2}{h} \end{bmatrix} \begin{bmatrix} x_e \\ y_e \end{bmatrix} \tag{1}$$

where,

$$x_e = \begin{bmatrix} \left(X_L - l^d \cos(\phi^d + \theta_L) - X_F\right) \cos\theta_F \\ +\left(Y_L - l^d \sin(\phi^d + \theta_L) - Y_F\right) \sin\theta_F \end{bmatrix} \tag{2}$$

$$y_e = \begin{bmatrix} -\left(X_L - l^d \cos(\phi^d + \theta_L) - X_F\right) \sin\theta_F \\ +\left(Y_L - l^d \sin(\phi^d + \theta_L) - Y_F\right) \cos\theta_F \end{bmatrix} \tag{3}$$

being the positional error between the leader and follower robots and k_1 and k_2 are controller gains that are constant positive integers greater than zero, which guarantee the system stability.

3.2. Geometric Controller during deadlock situation

As the deadlock situation arises as mentioned in section 1, one possible and logical solution is to reverse i.e., drive the entire robot system in a backward direction to a safer distance without losing its geometric patterns. In most of the studies found in the literature and the tracking controller illustrated above, motion control is difficult because the kinematic model is represented by highly nonlinear equations. Further, the motion planning in the backward direction of robots is an open-loop unstable control problem and formulated as a trajectory following problem rather than the control of independent, generalized coordinates as addressed in (Kuppan Chetty et. al., 2011, 2012). However, this system fails, when the entire focus is on reversing the robot platoons without losing their geometric pattern and maintaining the desired separation and orientation. The main disadvantage is that the presence of a set of non-linear equations in the tracking controller and linearizing the models to obtain the reference trajectory for the robots makes it complex to understand and increases the computational cost as well as hinders the performance of the system.

To address this issue, a tracking controller is proposed using a simple geometric relationship between the robot using the linear and angular separation, l_d and φ_d. We know that there are two critical parameters l and φ that determine the geometric shape of the robot formation and it does not change the pattern throughout its fly even if it is driven in forward or backward motion. Also, we know that the parameters that govern the motion of the robot are the translational and rotational velocities v_L, ω_L and v_F, ω_F respectively. The robots are driven in any given trajectory based on controlling the velocities that govern a rolling motion on the wheels of the robots and it rotates about a point known as the Instantaneous Centre of Curvature (ICC)/Instantaneous Centre of Radius (ICR):

$$ICR = \frac{v}{\omega} \tag{4}$$

From Figures 2 and 3, it could be observed that ICC and ICR play an important role in making the robots to remain in the formation keeping the required linear and angular separation while following a curvilinear trajectory. The ICC of the leader robot is given by the distance between point O and the axis of R_1 and the ICC/ICR of the robot designated as a follower is given by the distance between point O and the axis of R_2 respectively. The ICC/ICR of the robots designated as leader and follower is determined as in equation (5):

$$ICR_L = \frac{v_L}{\omega_L} \text{and } ICR_F = \frac{v_F}{\omega_F} \quad (5)$$

While in tightly coupled formation, Robot R_2 designated as a follower is required to follow the robot R_1 in a defined linear and angular separation. From the geometric aspect and the literature of trajectory tracking between the robots, it could be observed that the ICR of the robots designated as follower arranged in any geometric pattern with the desired linear and angular separation could be found using the law of sines as

$$ICR_F = ICR_L - l^d \, sin(\varphi^d) \quad (6)$$

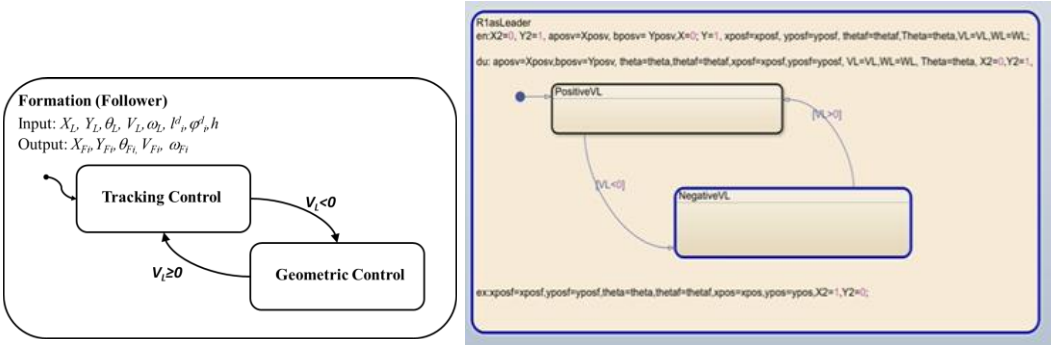
Substituting equation (5) in the equation, it becomes

$$\frac{v_F}{\omega_F} = \frac{v_L}{\omega_L} - l^d \, sin(\,\varphi^d) \quad (7)$$

When, v_L, ω_L, l^d, φ^d is known, then assuming either v_L=v_F or ω_L=ω_F, the required wheel velocities of the follower robot could be determined which positions the follower robot in the desired separation with respect to the leader mimicking its motion behavior. This approach of estimating the wheel velocities, converts the backward motion problem from the trajectory tracking problem to the trajectory following problem and eliminates the set of nonlinear equations, and makes the computations simple.

4. SIMULATION STUDIES

Simulation studies are carried out to investigate the performance of the developed backward motion tracking controller. Simulation studies are carried out in a MATLAB/ STATEFLOW environment. State flow is chosen because, it is an interactive graphical design and development tool that works with Simulink to model and simulate complex systems modeled as finite state machines, also called reactive event-driven systems based on motion states of the robots. In this work, the complex multi-robot system is modeled as a layered reactive system, where the inherent behaviors work on individual goals asynchronously, upon integration used to achieve the overall task of stable formation without losing its geometric patterns. The major advantage of such an approach is the functional interactions between the state machines are investigated in terms of state transitions in the system either with discrete behaviors modeled by Finite State Machines or the continuous behaviors modeled algebraically using differential equations. Therefore, this work follows the similar method called state-based modeling addressed in (Kuppan Chetty et al., 2011, 2012), to model and simulate the individual task achieving behaviors mentioned in Figure 1.



(a) **(b)**

Fig. 4. (a) Behavior implementation in State flow; (b) Response of switching between control between behaviors

The detailed implementation of the layered control approach in a state flow environment could be found in (Kuppan Chetty et al., 2011, 2012). Figure 4 shows the implementation of the formation control behavior of the multi-robot system, where the task achieving behaviors such as the tracking controller and the geometric controller responsible for driving the robots in forward and backward directions are modeled as temporal states. The lines with the arrow-heads between the states represent the state transitions that are necessary to provide the interconnections between the states/behaviors. The transitions from the tracking controller and the geometric controller occur based on the explicit information of the leader robots wheel velocities received and used as the state transition conditions. The arrow with a dotted head indicates the default state while the controller enters the formation motion state. The necessary information such as the postures and velocities of the robots in the group are received as explicit information through inter-robot communication.

The idea of switching between both the formation state is, whenever the velocities of the leader robot are less than a positive integer, i.e. driven in a negative direction, the controller switches the state from the generalized tracking controller to the geometric controller to drive the robots designated as a follower to mimic the behavior of the leader robot. This is shown in Figure 4 (b) as the result of switching between the behaviors in real-time simulation studies in a state flow environment. The necessary entry variables and exit variables, response output of the corresponding behavior, separation errors, and motor control data obtained as the results are recorded. The required interfaces for the statecharts to the inputs and outputs are created in the Simulink environments. The required sensor inputs for perception by the robots are created as discrete events and data in the signal builder of the Simulink environment as given in (Kuppan Chetty et al., 2011, 2012).

Simulation studies are carried out for 200 units in time frame with three robots R_1, R_2, and R_3 navigating the environment of interest in a wedge-shaped geometric pattern. At any instance of time Robot R_1 is considered as the leader robot, and R_2, R_3 are designated as follower robots, tracking the leader with the desired linear and angular separation of 1000 mm and 135° and 225° respectively placing the follower robots in either side of the leader, respectively. Leader navigates the environment with the lower-level navigational behaviors with the piecewise constant translational and rotational velocity of ±150 mm/s and ±3°/s making an ICC/ICR of 2.9 m.

The leader robot is made to reverse its direction if all the robot experiences obstacles on its path and this condition are simulated in the signal builder that all sensors provide a logically high signal at the same instant. The dimensional parameters of the differential drive kinematics of the *Pioneer P3DX* open-ended robot research platform are considered. The initial values of the robots R_1, R_2 and R_3 are given and ensured that the postures of the R_2 and R_3 are at arbitrary positions to test the efficiency of the tracking controller to make the robots remain in the stable formation. Postures and wheel velocities of all the robots are taken and logged as the output in the data logger. The wheel velocities of all the robots are constrained and bounded by the conditions $\upsilon < \upsilon_{max} <\pm\ 300\ mm/s$ and $\omega < \omega_{max} < \pm 40\ °/s$, considering the kinematics of the P3DX robot research platform.

5. RESULTS AND DISCUSSION

Figure 5 to 7 illustrates the results that have been obtained as the performance of the existing tracking controller and proposed geometric controller, controlling the robot group is tightly coupled wedge-shaped geometric pattern during forward and backward motion robots. Figure 5 (a), Figure 6 (a), and Figure 7 (a) show the performance of the generalized tracking controller in the backward motion while navigating the environment. Similarly, Figure. 5 (b), Figure 6 (b), and Figure 7 (b) show the performance of the geometric controller in the backward motion. It is also observed that the switching control strategy developed using the behavior-based approach effectively switches its behavior from the generalized tracking to the proposed geometric tracking when all the robots experience the obstacles and driving in the backward motion.

Figure 5 shows the trajectory of the robots during the fly, navigating the environment by changing its direction of motion. The efficiency of the generalized tracking controller could be observed from both (a) and (b), whereby it makes the robots remain in the tightly coupled formation during the fly. However, it could be observed from (a) that the tracking controller fails to make the robots remain in the formation during backward motion with maximum separation errors and goes into the uncontrollable state, which is indicated by a dotted rectangle in Figure 5 (a).

This is because the linearized model makes the rotational velocities of the robot R_2 and R_3 go beyond the constraint values. From Figure 5 (b), it could be observed that the geometric controller safely drives the robots in the backward motion keeping its tight geometric pattern, as this works by calculating the wheel velocities of the follower robots by the *ICC/ICR* relationship with its leader robot as given in equation (7) and guides the robot without losing its geometric pattern by mimicking the motion of the leader. It could also be observed from Figure 4 (b) that the switching control strategy switches from the geometric controller to the tracking controller once the backward motion is completed i.e., wandering to a safer distance to avoid the obstacle.

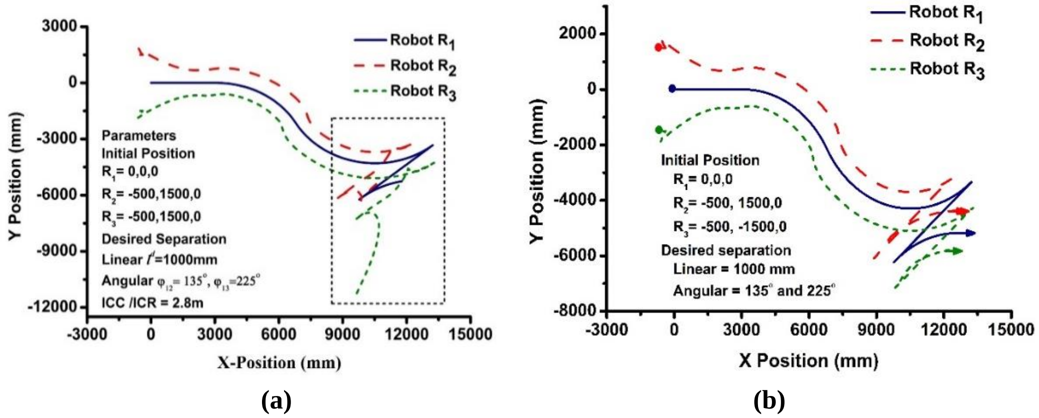


Fig. 5. (a) Trajectory of robots in wedge-shaped formation exhibiting uncontrolled motion using a tracking controller; (b) The trajectory of robots in wedge-shaped formation exhibiting controlled motion using proposed controller during backward motion

Figure 6 (a) and (b) illustrates desired linear and angular separation between the robots, where it could be observed that the generalized tracking controller could not be able to guide the robots to remain in the formation during backward motion, However, the geometric controller makes the robot to remain in the formation during its fly.

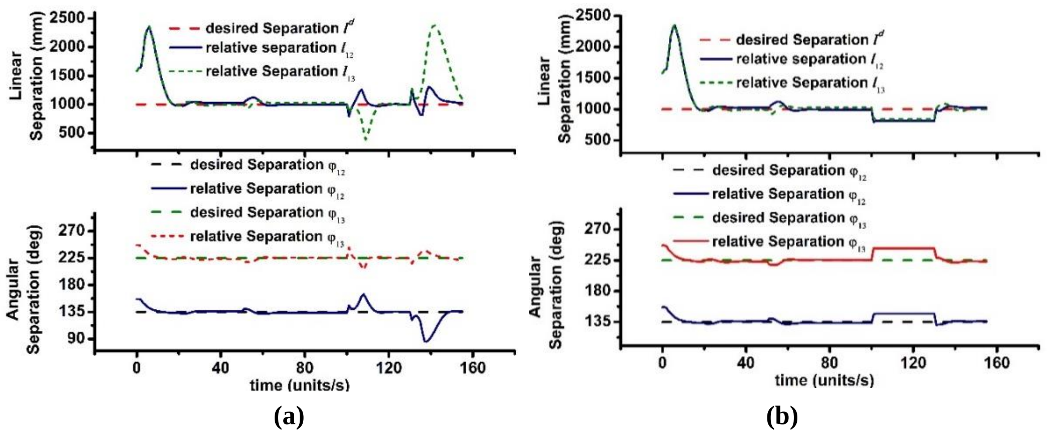
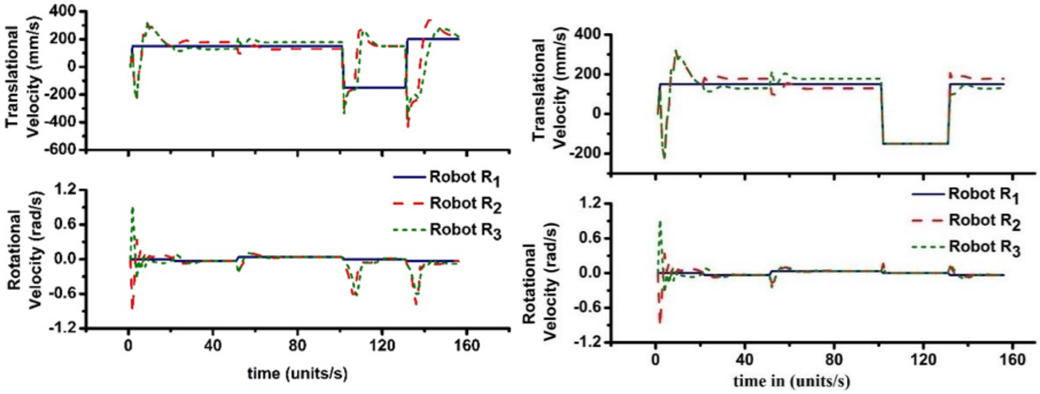


Fig. 6. (a) Linear and angular separation of robots in wedge-shaped formation exhibiting loss of formation using generalized tracking controller; (b) Linear and angular separation of robots in wedge-shaped formation exhibiting tightly coupled separation using proposed controller during backward motion



(a) **(b)**

Fig. 7. (a) Velocity profiles of robots in collateral formation exhibiting uncontrolled velocities using a tracking controller; (b) Velocity profiles of robots in collateral formation exhibiting controlled velocities between the robots using the proposed controller during backward motion

The velocity profiles of the robots are illustrated in Figure 7. It is also observed from Figure 7 (a) that the generalized tracking controller, lacks to keep the rotational velocity in the constrained limit as the sudden change in the direction of motion causes a step-change in the input and increases the tracking error. However, the proposed geometric controller keeps the robot in the tightly coupled formation where it estimates the rotational velocity by the ICC/ICR relationship given in equation (7) and by mimicking the leader's translational velocity.

Further simulations have been carried out by keeping the robots in various geometric formation topologies such as inline and collateral, and it is found out that the proposed geometric controller guides the robot in the defined geometric pattern in the backward motion with the linear, angular, and orientation errors less than ±2%, ±0.8%, and ±1.3% respectively.

6. CONCLUSION AND FUTURE SCOPE

In this work, a switching control strategy in a behavior-based approach where the behavior or motion states of the robots are switched to achieve the task of driving the robots in the backward motion with the tightly coupled formation is addressed. A generalized closed-loop tracking controller considering the leader referenced model is used for the robots to remain in the formation while navigating the environments. A simple geometric controller using the Instantaneous Centre of Radius (ICR) is developed to drive the robot in the backward motion during the deadlock situated is developed and presented. State-Based Modelling is used to model the behaviors/motion states of the proposed approach in MATLAB/STATEFLOW environment. Simulation studies are carried out to test the performance and error dynamics of the proposed approach combining the formation, navigation, and backward motion of the robots in all geometric patterns of formation. The simulation results show that the proposed closed-loop controller based on geometric approach efficiently drives the robots in the backward motion with stable formation without perturbing the formation of the robots, with the linear, angular, and orientation errors less than ±2%, ±0.8%, and ±1.3% respectively, during the fly. It is also planned to conduct experiments virtually in Webots virtual simulation environment and in real-time using differential drive pioneer P3DX robot research platforms in an environment filled with multiple obstacles.

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