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Trajectory tracking and control of differential drive robot for predefined regular geometrical path

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Abstract

Trajectories made by concatenating straight motion and in place turning primitive are one that can be easily followed by a differential drive robot. This paper presents trajectory tracking and control of differential drive robots along a predefined regular geometrical path made up of these primitives. A control algorithm was developed to control the robot along different trajectories. The algorithm takes user input from a user interface through which one can select the type of trajectory, dimensions of the trajectory and tracking velocity. Simulations were carried out to obtain the trajectory tracked by the robot using commercial available software MATLAB, Release 2010. Experiments were conducted for tracking regular trajectories such as Triangular, Rectangular and Square and these experimental results were found to be in good agreement with the simulation results.

Keywords: *mobile robot; differential drive; motion primitive; graphical user interface; simulation; trajectory*

1.Introduction

Need for the mobile robots and intelligent autonomous vehicles are increasing in different sectors from industry to medical to military. Differential wheels are one of the most widely used structures of locomotion for such autonomous mobile ground robots and ground vehicles. To attain full autonomy several aspects like sensing, path planning, trajectory tracking and control, self-localization etc have to be addressed. In this scenario path planning trajectory tracking and control of differential drive robots and vehicles is a problem of great importance.

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Differential drive robot has independently actuated right and left wheels. There may be an additional passive wheel in the front for smooth movement of the robot. The motion of the robot is controlled by controlling the left and right rear wheel velocities V_L and V_R. Rolling of rear wheels without slipping makes the velocity of the robot to be orthogonal to the axle connecting the rear wheels.This induces nonholonomic constraint which makes it difficult to control the robot. The summary of developments in nonholonomic control problem was discussed by Ilya K et al [1]. Model of a differential drive robot is shown in Fig. 1.

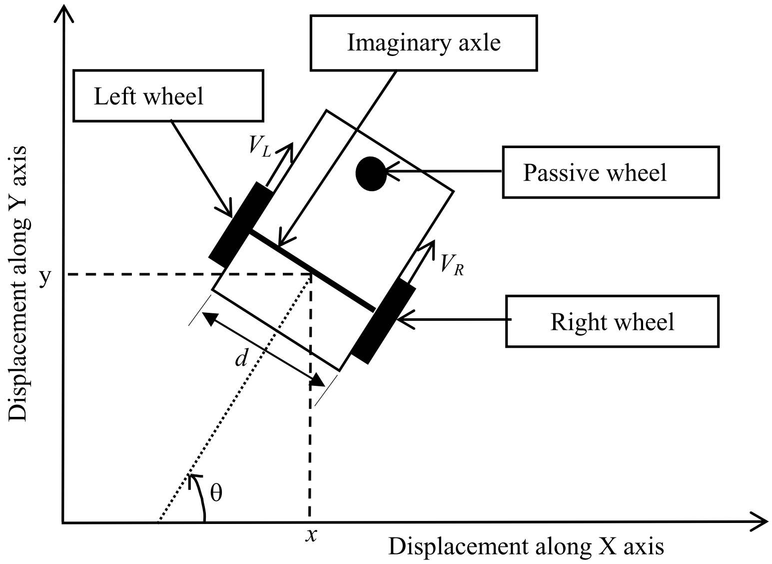


Fig .1. Model of a differential drive robot.

General kinematic equation for motion of the robot is given by Eq. 1. The translational velocity (V) and the angular velocity (ω) of the robot is given by Eq. 2 and Eq. 3 respectively. Here the robot velocity is considered as the velocity of rear axle midpoint of the robot assuming that an imaginary axle is connecting the rear wheels.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V \\ \omega \end{bmatrix} \tag{1}$$

$$V = (V_R + V_L)/2 \tag{2}$$

$$\omega = (V_R - V_L)/d \tag{3}$$

Different methods for motion planning and trajectory control of nonholonomic systems especially differential drive robots have been mentioned in literatures. Motion planning of robots in high dimensional static workspace is solved using probabilistic road maps [2]. The path planner developed in the work computes collision-free path for robot moving among stationary obstacle. The problem of motion planning of car like robot among stationary obstacle was done by recursive subdivision and optimization of a collision free path [3]. The subdivision and optimization of the path was done considering the motion constraints of the robot so that the path generated can be followed by the robot. Nonholonomic visibility graph was used for computing shortest path with minimum wheel rotation for a disc shaped differential drive mobile robot [4]. Bezier curve passing through the designated points was used for path generation of automated vehicles [5].

Single-query nonholonomic path planning problem can be solved with Rapidly-exploring Random Trees (RRT) [6]. The RRT algorithm has advantage of solving general nonholonomic problem. RRTs are specifically designed to handle nonholonomic constraints including dynamics for systems with higher degree of freedom. Many of the commercial motion planning softwares were developed based on this approach. The pre-processing was avoided in RRT thus making it easy to implement. An advanced version of RRT called RRT-connect [7] is used to solve the problem of motion planning by incrementally building two RRTs rooted at the start and goal locations. The two trees will grow towards each other until they are connected. Path planning and control of differential drive robots and car-like robots in narrow environments was achieved with the help of this RRT based global planner [8]. The global planner will reduce the free space to regions which are reachable by concatenation of simple motion primitives like straight motion and in place turning. The trajectory tracking control was shown using simulations. The path generated by the RRT based planner is shown in Fig. 2. Many of the existing software uses RRT based algorithm to generate feasible trajectories for differential drive robots.

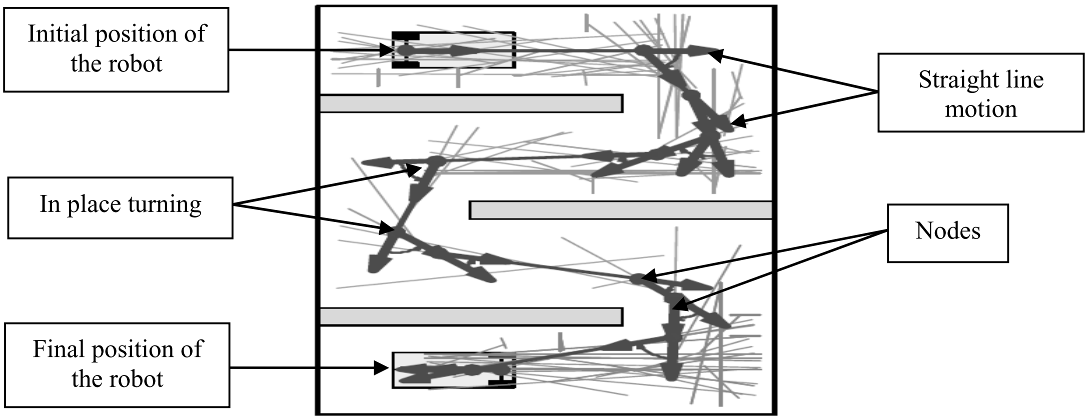


Fig. 2. Path generated by Rapidly-exploring random trees based planner [8].

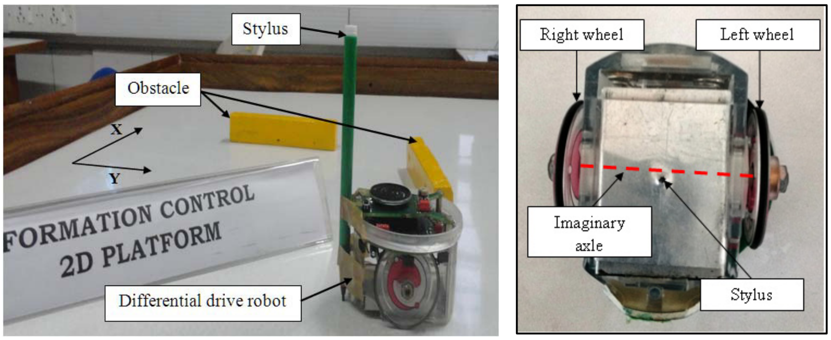
Several methods for trajectory tracking were discussed in literatures. The trajectory tracking of electrically driven nonholonomic mobile robot was considered by Bong et al. [9]. In this work dynamic control approach was used for the controller design. Actuator dynamics was also considered while designing the controller. This makes the control strategy complex and difficult to design. Fuzzy Logic Controller (FLC) which automatically follows discrete waypoints can be used for controlling a four wheeled robot along a trajectory [10]. The rules of FLC can be based on an analogy with a human driving the car. Ouyang et al. proposed Proportional Derivative (PD) with sliding mode control for trajectory tracking of robotic system [11]. Nonlinear adaptive state feedback controller was proposed for steering a quadrotor vehicle along a trajectory [12].The controller stabilizes the system in case of a force disturbance. Gaurav et al. presented conditions for target tracking of mobile targets with range-only information [13]. Graphical User Interface (GUI) is generally used for human robot interaction for automatic navigation. Semiotic engineering can be applied for developing GUI for controlling a mobile robot [14].

Majority of the literature have considered path planning problem. Controlling a real robot along the path generated by the path planning software was mentioned in very few cases. In many of the literature trajectory tracking were shown using simulations rather than real experiments. Controlling a real robot along a predefined trajectory generated by a path planning software is one of the least studied areas. Therefore this paper presents trajectory tracking and control of differential drive robots along regular trajectories made up of straight motion and in place turning primitive. Such trajectories can be generated by a path planning software like RRT based global planner which is already discussed in this paper. A simple control algorithm was developed to control the robot along predefined regular trajectories such as triangular trajectory, rectangular trajectory and square trajectory. The same control strategy can also be used for controlling the robot along much more complex trajectories.

This paper is organized as follows: Experimental setup and the control strategy which is explained in Section 2. Section 3 presents the result and discussion. Conclusion and direction of future work are summarized in Section 4.

2.Experimental setup

The experimental setup consists of a differential drive robot, which moves over a 2-D platform as shown in Fig. 3(a). A stylus as attached to the robot used to sketch the trajectory followed by the robot. Once robot reaches the destination one can inspect the trajectory with the help of sketch made by stylus. Two separate set of experiments were conducted first attaching the stylus to the outer edge of the robot and then attaching the stylus near to the centre of the imaginary axle of the robot. This will allow one to see the difference in the path traced by the stylus when placed at different locations. Fig. 3(a) shows stylus placed at outer edge of the robot and Fig. 3(b) shows stylus placed near to centre of the imaginary axle. Also simulation has been carried out to simulate the path traced by the differential drive robot using commercial available software MATLAB, Release 2010 in both cases. All the experiments were conducted using differential drive robot shown in Fig. 3(a). The specification of the robot is given in Table 1.



(a) (b)

Fig. 3. Experimental setup.

Table 1. Specification of differential drive robot

Feature	Technical specification
Size, Weight	70 mm diameter, 55 mm height, 150 g
Processor	dsPIC30F6014A @ 60 MHz,16 bit microcontroller
Motors	Two stepper motors with a gear reduction ratio 50:1, resolution: 0.13 mm
Speed	Max: 150 mm/s
Wireless	Bluetooth for robot-computer interface and robot-robot wireless communications
Battery	5Wh LiION rechargeable and removable battery

A control algorithm was developed for trajectory control of the robot. The flow chart of the algorithm is shown in Fig. 4. The algorithm was implemented on a remote computer and robot was connected to the computer through Bluetooth. Control algorithm generates commands to control the robot and communicate the commands to the robot using this Bluetooth connection. The processor of the robot will act as a slave to the computer and will obey the commands send from the desktop.

To track a rectangular trajectory of length 200 mm and breadth 150 mm algorithm generates following control commands:

a) Move forward 200 mm and turn 90^0.
b) Move forward 150 mm and turn 90^0.
c) Move forward 200 mm and turn 90^0.
d) Move 150 mm and again turn 90^0.

This will complete the rectangle and robot will reach back to its starting position. Fig. 5 shows the developed Graphical User Interface (GUI). The user with the help of this interface running on the remote computer can change different parameters like velocity of the robot, trajectory to be generated, dimension of the trajectory etc .The algorithm take these inputs and give necessary control signals to track the required trajectory.

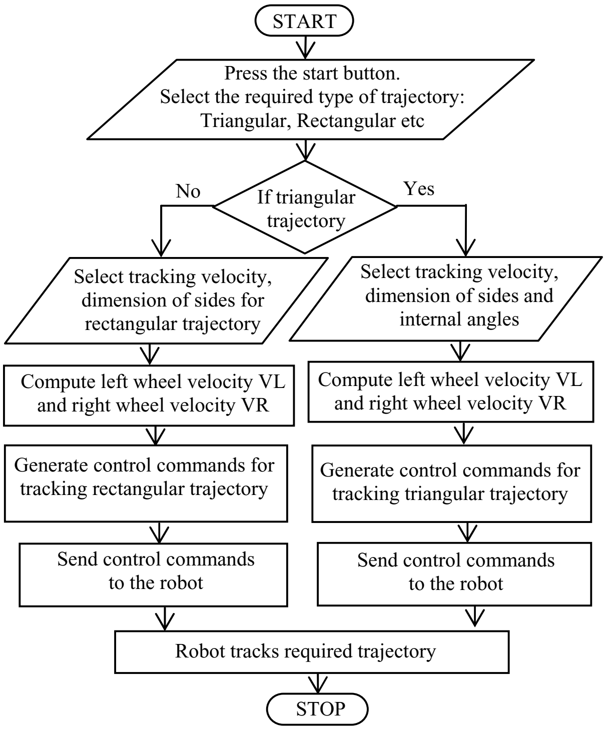


Fig. 4. Flow chart of control algorithm.

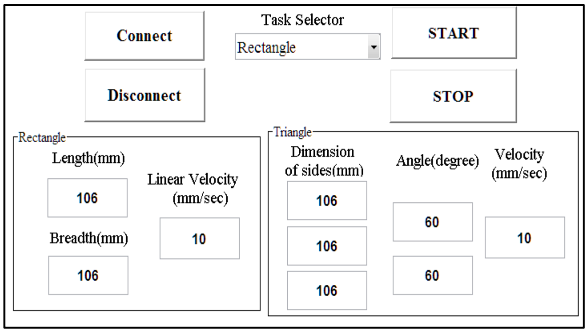


Fig. 5. Graphical user interface developed for human- robot interaction.

3.Results and discussion

Simulations were carried out to obtain the path tracked by stylus while centre of axle of the robot follows predefined trajectories such as triangular trajectory, rectangular trajectory and square trajectory. Difference in the path traced when stylus is placed at different locations on the robot is also studied using the simulations. For the simulation wheels of the robot were assumed to be rolling without slipping. Experiments were conducted to verify the simulation results. Regular trajectories such as triangular trajectory, rectangular trajectory and square trajectory were tracked using the robot. The results are compared to see the improvement in the path traced by stylus by placing stylus near to centre of the imaginary axle. Preliminary experimental results are available [15].

3.1 Triangular trajectory

Equilateral triangle of sides 150 mm was tracked with a tracking velocity of 10 mm/s with the help of the developed controller. Fig. 6(a) shows the simulated trajectory for stylus kept near to the outer edge of the robot and Fig. 6(b) shows the corresponding trajectory traced by stylus during the experiment. Fig. 6(c) shows the simulated trajectory for stylus kept near to centre of imaginary axle of the robot and Fig. 6(d) shows the actual trajectory traced by the stylus during the experiment.

It was observed that the robot is tracking the triangular trajectory as expected. The problem of arcs produced at nodes (corners/vertices) due to turning radius of stylus and error in angle turned at node occurred for stylus kept near to outer edge of the robot. For stylus kept near to centre of axle the arcs produced was very small and can be neglected Fig. 6(d). The error in the angle turned during the in-place turning step can get accumulated if large numbers of in place turning steps are used for generating a complex geometry.

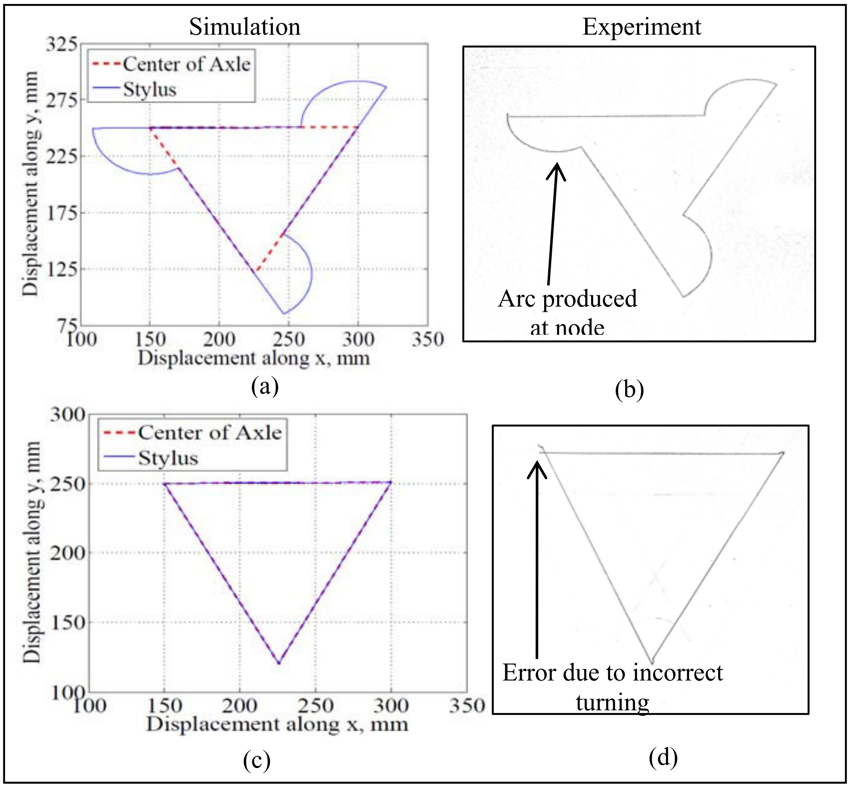


Fig. 6. Triangular trajectory tracked by the robot.

3.2 Rectangular trajectory

Rectangle of length 150 mm and breadth 125 mm was tracked with a tracking velocity of 10 mm/s. Fig. 7(a) shows the simulated trajectory for stylus kept near to the outer edge of the robot and Fig. 7(b) shows the actual trajectory traced by the stylus during the experiment. Fig. 7(c) shows the simulated trajectory for stylus kept near to centre of axle of the robot and Fig. 7(d) shows the corresponding trajectory traced by the stylus during the experiment. The rectangle produced experimentally has perpendicularity error. The problem of arcs produced at nodes also occurred for stylus kept away from centre of axle. The perpendicularity error was due to the incorrect angle turned by robot while performing in place turning step. This error can be reduced by reducing the angular velocity of turning by which the robot will get time to respond to control signal before the angle exceeds the required angle. This error can also be reduced by incorporating feedback mechanism.

The circular arcs produced at nodes Fig. 7(b) were due to inherent limitation of nonholonomic system to make a perfect turn. Differential drive robot can make perfect turn only with respect to centre of axle as shown in Fig. 7(a) and not with respect to any other points. Since stylus is kept away from the centre of axle, it will have a turning radius, which is equal to the distance from centre of axle. This result in circular arcs generated at the corners. This problem can be eliminated by placing the stylus at centre of axle.

3.3 Square trajectory

Square being a special case of rectangle, the same algorithm can be used to track both rectangular and square trajectory. Square trajectory of length 125 mm by 125 mm was tracked at a tracking velocity of 10mm/s. Fig. 8(a) shows the simulated trajectory for stylus kept near to the outer edge of the robot and Fig. 8(b) shows the corresponding trajectory tracked by the stylus during experiment. Fig. 8(c) shows the simulated trajectory for stylus kept near to centre of imaginary axle of the robot and Fig. 8(d) shows the corresponding trajectory traced by the stylus during the experiment. The square trajectory tracked by robot has error similar to that of rectangular trajectory.

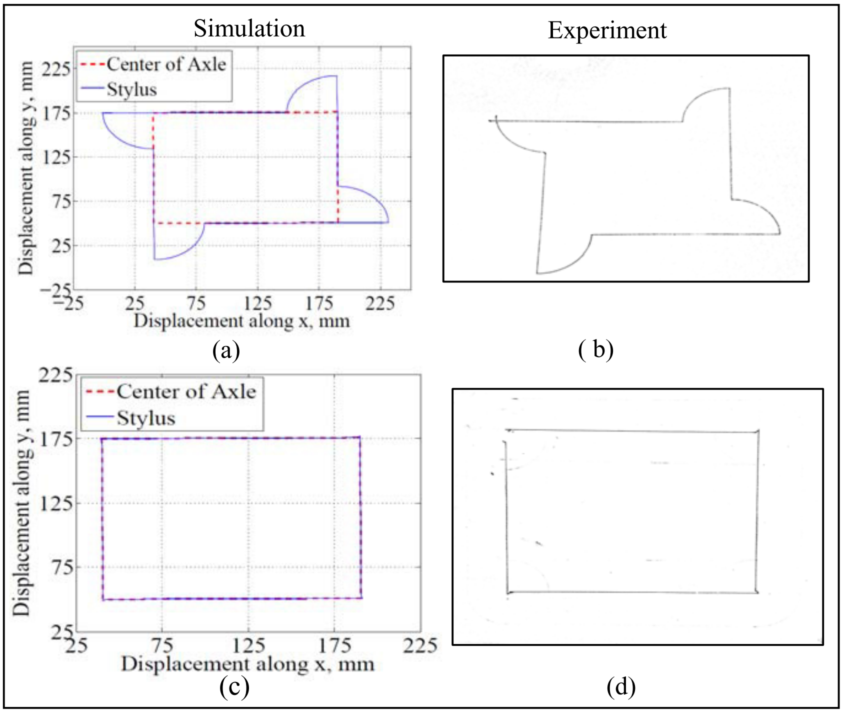


Fig. 7. Rectangular trajectory tracked by the robot.

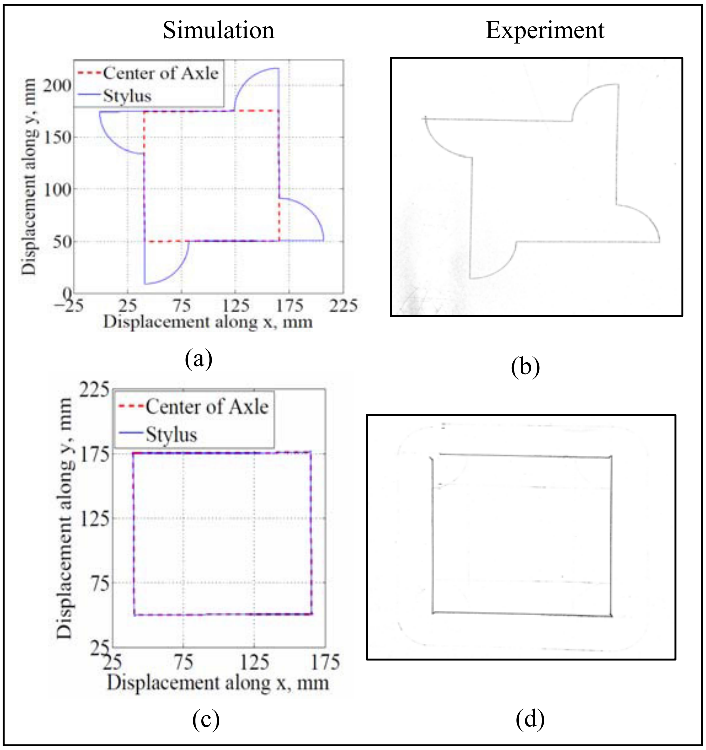


Fig. 8. Square trajectory tracked by the robot.

4.Conclusions

Trajectory tracking and control of differential drive robots along different regular trajectories was introduced. The control algorithm developed in this work can be used for tracking the trajectories made up of straight motion and in place turning primitive.

The conclusions are summarized as given below:

- A control algorithm was developed for trajectory tracking control of differential drive robots.
- The algorithm developed is tested for controlling the robot along different regular geometrical trajectories such as triangular trajectory, rectangular trajectory and square trajectory.
- Arcs produced at nodes due to turning radius of stylus and error in angle turned at nodes is found to be the main limitations of current control strategy.
- The error in angle turned at nodes can be reduced by reducing the turning speed thereby giving time for robot to respond to the control signal. This error can also be reduced by incorporating feedback mechanism.
- The problem of circular arcs at nodes due to turning radius of stylus can be removed by placing the stylus at centre of axle.

The future work includes the development of a control algorithm to reduce the error in the angle turned by the differential drive robot at nodes as seen in this paper which will be more realistic in the present scenario.

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