Proc. of the 2011 6th International Conference on System of Systems Engineering, Albuquerque, New Mexico, USA - June 27-30, 2011

# Coordinated Traffic Scheduling for Communicating Mobile Robots

Anjan Kumar Ray *, Martin McGinnity *, Laxmidhar Behera †, Sonya Coleman *, Mo Jamshidi ‡
*Intelligent Systems Research Centre, University of Ulster, BT48 7JL, UK
†Department of Electrical Engineering, Indian Institute of Technology, Kanpur 208016, INDIA
‡University of Texas, San Antonio and the ACE Center, Texas 78249, USA
( e-mail: ak.ray@ulster.ac.uk, tm.mcginnity@ulster.ac.uk, lbehera@iitk.ac.in,
sa.coleman@ulster.ac.uk, moj@wacong.org)

***Abstract*— In this paper, a multi-robot networking paradigm is presented. This provides a general framework for coordination among a group of robots. An experiment is conducted showing the effectiveness of the developed network paradigm where a robot controls a group of robots. A coordinated traffic scheduling method is proposed for mobile robots. The aim is to build onboard knowledge for autonomous robots without ranging sensors (sonar or laser range finder) and/or cameras. In this work, more emphasis is given on the exploration of interactions between a pair of robots. The robots share their positions, orientations and safety information and the decision of a robot depends on interactions of the forward safe paths (FSPs) of these robots. The properties of intersection of two straight lines are used to classify different situations. The proposed method is discussed in details with various combinations of scenarios. Simulation results are presented to show the effectiveness of the proposed method.***

## I. Introduction

Automatic traffic scheduling is an important research issue for mobile robots [1], [2]. Several methods are available in literatures for human operated vehicles [3], [4]. Bender summarized various issues related to autonomous path planning of vehicles [3]. Further autonomy is achievable with vehicular ad-hoc networking where vehicles exchange and process their positional information [5], [6]. Fox *et al.* had shown that multiple robots can localize themselves faster and more accurately by exchanging their positional information [7]. A group of autonomous robots navigates in a controlled or an unknown environment [8]. These robots need to avoid several obstacles as well as other robots along their paths. Forward safe path (FSP) based obstacle avoidance and path planning schemes were presented in [9]. In this work, we address an issue where a robot without having ranging sensors shares its positional information with other robots to avoid collision. Here, more emphasis is given on the exploration of different interactions. A traffic scheduling scheme based on the FSP interactions is proposed where robots share their positions, orientations, length and width of the FSPs. It aims at simplifying navigation of robots through traffic coordination. Coordination among a group of robots requires a shared network paradigm. The objective of network control is to control a group of robots to achieve some global tasks. The task is to develop adequate communication and computational models for the collaborating robots. Here, we present a multi-robot network paradigm to share resources which can be utilized in different multi-robot application areas.

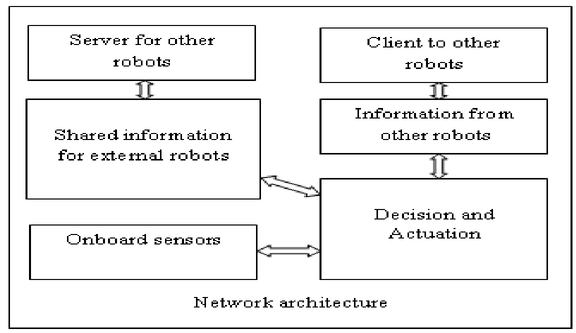


Fig. 1. Network architecture of a robot within multi-robot paradigm

In section II, we present the developed multi-robot network paradigm. Motivation for coordinated traffic scheduling is presented in section III. In section IV, the FSP model for traffic scheduling is introduced. The scheduling issues are discussed in section V. The proposed method is described in section VI. It is discussed with different scenarios along with simulation results in section VII. The overall conclusion and future direction are presented in section VIII.

## II. Development of multi-robot network

A group of robots is useful to accomplish coordinated tasks such as search, rescue, military application etc. Each robot in a group can facilitate other robots with its shared resources of information.

A general network paradigm is developed for a multi-robot system using ArNetworking library of Advanced Robot Interface for Applications (ARIA) from $MobileRobot^{TM}$. It provides the following facilities: Each robot acts as a server of different information for other robots; each robot can request information from other robots; a robot can be connected by any individual robot or a group of robots; a robot can connect to an individual robot or a group of robots; a robot can switch among server robots autonomously depending on requirements; each robot continues its own task while serving requests from other robots. The adapted structure of individual robot

978-1-61284-782-5/11/$26.00 ©2011 Crown 

Fig. 2. A mobile robot controls a group of robots using the developed multi-robot network

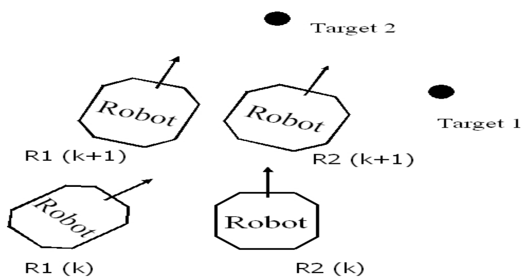


Fig. 3. Problem of considering another robot as an obstacle

is shown in Fig. 1. An experiment is conducted where one Pioneer P3-Dx controls a group of other robots for translational motion (Fig. 2). In this case, the controlling robot connects to the other robots, sends movement commands and extracts on-board data from these robots (x-y positions, orientations, and velocity). So a robot can act autonomously or be controlled by another robot. Likewise, such shared information are required for a coordinated traffic scheduling.

## III. Motivation for traffic scheduling

Let Target 1 and Target 2 are associated with robots R1 and R2 respectively and R1 detects R2 at its right side at the $k$-th time (Fig. 3). As both of them move, R1 takes a left turn and R2 takes a right turn to avoid collision. Configurations of these robots are shown for the $(k+1)$-th time. These robots will continue to hinder each other. But these robots can have simplified interactions if either one of them stops to provide a safe passage to the other one. So, a proper traffic schedule can simplify the situation.

Fig. 4 shows configurations of four robots. The left and right sided robots are equidistant from the central robot and the right sided robots have same orientations. The robots at the left side and the lower right side will not collide with the central robot. But, the robot at the upper right side may collide with the central robot. It seems that separation distances, relative positions and orientations of robots are misleading as indications of impending collision in various situations. So, there is a need of appropriate representations

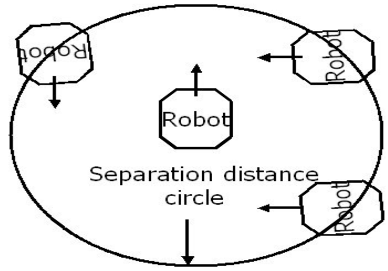


Fig. 4. Complexity of traffic scheduling with the separation and orientation information

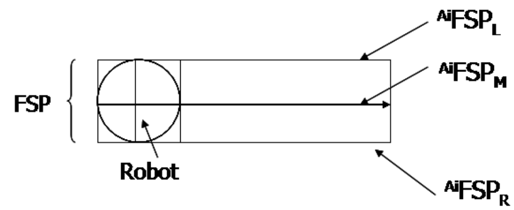


Fig. 5. FSP model of a robot $A_i$ for traffic scheduling

of information for traffic scheduling.

## IV. FSP model

A FSP based path planning for mobile robot was presented in [9]. In this work, the concept is extended to a FSP based coordinated traffic scheduling for robots without ranging sensors. Fig. 5 shows a general representation of a robot $A_i$ in this scheme. Physical dimension and a safety clearance of a robot are covered by the FSP. The safety issues are described in [9]. The FSP has three limiting lines. They are the left sided limit ${}^{A_i}FSP_L$, central limit ${}^{A_i}FSP_M$ and right sided limit ${}^{A_i}FSP_R$. The length of the FSP depends on the safety clearance and velocity of the robot. This can be represented as

$$L({}^{A_i}FSP) = \xi^{A_i} v_{max} \Delta t \quad (1)$$

where, $L({}^{A_i}FSP)$ is the desired length of the FSP, ${}^{A_i}v_{max}$ is the maximum linear velocity of $A_i$, scaling factor $(\xi, \xi > 0)$ is any real number and $\Delta t$ is the sampling period for the traffic scheduling. A proper choice of $\xi$ can make the length proportionate to the robot's dynamic velocity.

Let, $[(x^i_{1R}, y^i_{1R}), (x^i_{2R}, y^i_{2R})]$, $[(x^i_{1M}, y^i_{1M}), (x^i_{2M}, y^i_{2M})]$ and $[(x^i_{1L}, y^i_{1L}), (x^i_{2L}, y^i_{2L})]$ represent the starting and ending coordinates of the right sided, central and left sided limiting lines of the FSP along the direction of motion of $A_i$. The center coordinates and orientation of $A_i$ at the $k$-th time are represented by $(x^i_R(k), y^i_R(k), \phi^i_R(k))$. The axes definitions, updates of center coordinates during movements are available in [9].

The core physical envelope $Base^{A_i}$ is defined around the robot using the FSP width limit. This is the FSP area covering the base of the robot (Fig. 5). A safety scaling factor $\epsilon_s$ and a safety clearance offset $\epsilon_r$ are used to model this envelope. It is given by

$$W(^{A_i}FSP) = 2\epsilon_s(R + \epsilon_r) \tag{2}$$

where, $R$ is the radius of $A_i$ covering its physical limits. The coordinates of the right sided FSP limiting line are updated by

$$\begin{aligned}
x^i_{1R} &= x^i_R(k) + \frac{W(^{A_i}FSP)}{\sqrt{2}}\cos(\phi^i_R(k) - \frac{\pi}{4}) && (3)\\
y^i_{1R} &= y^i_R(k) + \frac{W(^{A_i}FSP)}{\sqrt{2}}\sin(\phi^i_R(k) - \frac{\pi}{4}) && (4)\\
x^i_{2R} &= x^i_R(k) + \frac{a}{2}\cos(\phi^i_R(k) + \theta_R) && (5)\\
y^i_{2R} &= y^i_R(k) + \frac{a}{2}\sin(\phi^i_R(k) + \theta_R) && (6)\\
\theta_R &= \tan^{-1}\frac{a}{W(^{A_i}FSP)} && (7)\\
a &= 2L(^{A_i}FSP) - W(^{A_i}FSP) && (8)
\end{aligned}$$

The coordinates of the central limiting line are updated by

$$\begin{aligned}
x^i_{1M} &= x^i_R(k) + \frac{W(^{A_i}FSP)}{2}\cos(\phi^i_R(k) - \frac{\pi}{2}) && (9)\\
y^i_{1M} &= y^i_R(k) + \frac{W(^{A_i}FSP)}{2}\sin(\phi^i_R(k) - \frac{\pi}{2}) && (10)\\
x^i_{2M} &= x^i_R(k) + \frac{a}{2}\cos(\phi^i_R(k) + \frac{\pi}{2}) && (11)\\
y^i_{2M} &= y^i_R(k) + \frac{a}{2}\sin(\phi^i_R(k) + \frac{\pi}{2}) && (12)
\end{aligned}$$

The coordinates of the left sided limiting line are updated by

$$\begin{aligned}
x^i_{1L} &= x^i_R(k) + \frac{W(^{A_i}FSP)}{\sqrt{2}}\cos(\phi^i_R(k) - \frac{3\pi}{4}) && (13)\\
y^i_{1L} &= y^i_R(k) + \frac{W(^{A_i}FSP)}{\sqrt{2}}\sin(\phi^i_R(k) - \frac{3\pi}{4}) && (14)\\
x^i_{2L} &= x^i_R(k) + \frac{a}{2}\cos(\phi^i_R(k) + \theta_L) && (15)\\
y^i_{2L} &= y^i_R(k) + \frac{a}{2}\sin(\phi^i_R(k) + \theta_L) && (16)\\
\theta_L &= \pi - \theta_R && (17)
\end{aligned}$$

For simplicity of representation, $k$ is omitted in the following discussion.

## V. Issues with traffic scheduling

In this work, we explore different possibilities of interactions between a pair of robots $A_i$ and $A_j$ at a given time. Fig. 6 shows that the robot $A_i$ moves along the positive x-axis and $A_j$ comes from the right side of $A_i$. Both robots can move safely with configurations as per Figures 6 (i) (for current configurations only) and (viii). But in cases of (iv), (v), (vi) and (vii), $A_i$ cannot move further. In all other cases, either one of them can move further.

Fig. 7 shows that the FSP of $A_j$ can intersect the FSP of $A_i$ at different angles and locations. Depending on each configuration either one of them can move safely while the other needs to stop to avoid collision. For example, either one of them can move with configuration as shown in Fig. 7 (ii), but $A_j$ cannot move with configuration as shown in Fig. 7 (v). The robot $A_j$ can come from the left side of $A_i$ while $A_i$ moves along the negative x-axis (Fig. 8).

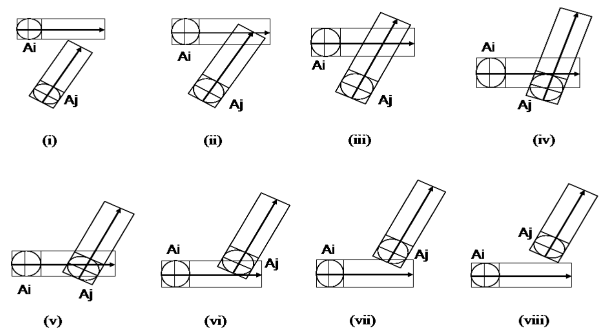


Fig. 6. Traffic situations: $A_j$ comes from the right side of $A_i$

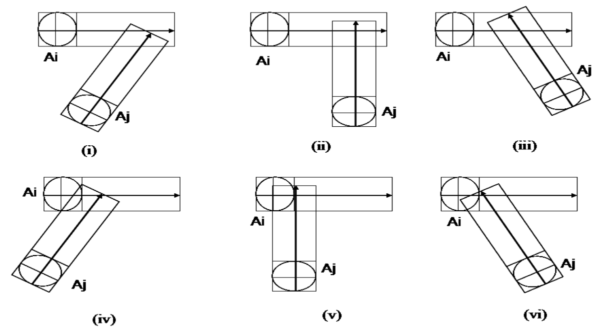


Fig. 7. Different angular and positional intersections of $A_i$ and $A_j$

The heading direction of $A_i$ is shown along the x-axis only while it may have all 4-quadrants heading directions leading to different situations.

## VI. Traffic scheduling method

The interactions of robots have some common features despite the level of complexities. A method based on limiting lines of the FSP is proposed to transfer this knowledge to robots. With this knowledge, a mobile robot can explore different possibilities of interactions with other mobile robot.

The properties of intersecting straight lines are used in this work. Fig. 9 shows the probable intersections of a line $\overleftrightarrow{CD}$ with a line segment $\overline{AB}$ at point $P$ with a ratio of $\frac{m}{n}$. The ratio is positive for case (i) and negative for cases (ii) and (iii). Furthermore, the value of the ratio is greater than 1 for case (ii) and less than 1 for case (iii).

A close study on Figures 6 through 8 reveals that $^{A_i}FSP_L$ and $^{A_i}FSP_R$ or their extensions intersect $^{A_j}FSP_M$ at various combinations of ratios. These ratios are represented by $R_L$ and $R_R$ respectively. Some interesting conclusion can be drawn from the value of $(R_S,\ S \equiv L, R)$.

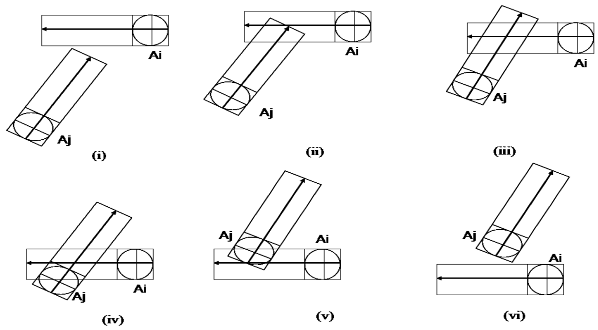


Fig. 8. Traffic situations: $A_j$ comes from the left side of $A_i$

$$
\begin{aligned}
R_S &> 0; \text{internal intersection} && (18)\\
R_S &< 0; \text{external intersection and} && (19)\\
|R_S| &> 1; \text{in the direction of motion of } A_j\\
|R_S| &< 1; \text{in the opposite direction of motion of } A_j
\end{aligned}
$$

There is a tricky issue here. $R_R$ and $R_L$ inform ratios at which the FSP of $A_i$ intersects the line segment of ${}^{A_j}FSP_M$. But, it is not confirmed whether these intersections are along the front side or backside of $A_i$. Even for front side, it is not confirmed whether the FSPs of $A_i$ and $A_j$ have overlapped or not.

Similarly, ${}^{A_j}FSP_M$ or its extension intersects ${}^{A_i}FSP_L$ and ${}^{A_i}FSP_R$ at various combinations of ratios represented by $R^j_{ML}$ and $R^j_{MR}$ respectively. There are some possibilities where the FSP of $A_i$ intersects $Base^{A_j}$. This reveals possibility of direct collision between them. Another set of conditions is developed which monitors such possibilities. This is represented as follows:

$$
\begin{aligned}
If \quad & (2m_S c_S - 2x^j_R - 2m_S y^j_R)^2 - 4(1+(m_S)^2)\\
& ((x^j_R)^2 + (y^j_R)^2 + (c_S)^2 - (r_R)^2) < 0\\
& {}^{A_i}FSP_S \bigcap Base^{A_j} = NULL \qquad (20)\\
If \quad & (2m_S c_S - 2x^j_R - 2m_S y^j_R)^2 - 4(1+(m_S)^2)\\
& ((x^j_R)^2 + (y^j_R)^2 + (c_S)^2 - (r_R)^2) > 0\\
& {}^{A_i}FSP_S \bigcap Base^{A_j} \neq NULL \qquad (21)
\end{aligned}
$$

where,

$$
\begin{aligned}
m_S &= \frac{y^i_{1S} - y^i_{2S}}{x^i_{1S} - x^i_{2S}} && (22)\\
c_S &= y^i_{1S} - m_S x^i_{1S} && (23)\\
r_R &= \epsilon_s(R + \epsilon_r) && (24)
\end{aligned}
$$

The condition in (20) confirms that there is no possibility of intersection of ${}^{A_i}FSP_S$ with physical envelope $Base^{A_j}$, whereas condition in (21) confirms that ${}^{A_i}FSP_S$ or its extension intersects the physical envelope $Base^{A_j}$. Here $(S \equiv L, R)$ stands for the left and right side of the FSP. Similar to (20) and (21), possibility of intersection

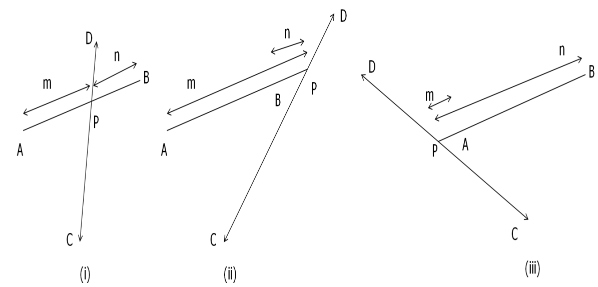


Fig. 9. Internal and external intersections of a line with a line segment

of ${}^{A_j}FSP_S$ and the physical envelope $Base^{A_i}$ can be achieved. The traffic rules based on the FSPs of a pair of robots $A_i$ and $A_j$ are as follows:

1) ($R_R < 0$ AND $R_L < 0$)
In this case, there is no possibility of collision according to current configurations. So, both $A_i$ and $A_j$ are safe to move further. For all other combinations of $R_R$ and $R_L$, FSP of $A_i$ or its extension intersects FSP of $A_j$. Followings are traffic rules for those cases:
2) $({}^{A_i}FSP_L \bigcap Base^{A_j} = NULL)$ AND $({}^{A_i}FSP_R \bigcap Base^{A_j} = NULL)$
This represents the fact that the FSP of $A_i$ does not pass through the physical limits of the robot. It confirms that if $A_i$ moves further, it will not collide with $A_j$. There are two sub-cases which confirm the decision of $A_j$.
a) $R^j_{ML} > 0$ OR $R^j_{MR} > 0$
This case confirms that the FSP $A_j$ is overlapped with the FSP of $A_i$. As $A_i$ moves further, $A_j$ should not move in this situation. This condition addresses the tricky issue as mentioned before and confirms that these intersections are at the front side of $A_i$.
b) $R^j_{ML} < 0$ AND $R^j_{MR} < 0$
This condition confirms that intersections of left and right limiting FSP of $A_i$ with the line segment of ${}^{A_j}FSP_M$ has happened in the opposite direction of motion of $A_i$ or along the direction of motion of $A_i$ but beyond the length of FSP. So, both $A_i$ and $A_j$ can move safely.
3) $({}^{A_i}FSP_L \bigcap Base^{A_j} \neq NULL)$ OR $({}^{A_i}FSP_R \bigcap Base^{A_j} \neq NULL)$
This represents the fact that either one or both of ${}^{A_i}FSP_L$ and ${}^{A_i}FSP_R$ or their extensions pass through physical dimension of $A_j$. But the intersection may occur on the opposite direction of motion of $A_i$. So, if $A_i$ moves further, it may collide with $A_j$ depending on the situation. There are two sub-cases which confirm the movement sequences of $A_i$ and $A_j$.
a) $R^j_{ML} > 0$ OR $R^j_{MR} > 0$
This case confirms that the FSP of $A_j$ is overlapped with the FSP of $A_i$. So, as a result, $A_i$ should not move in this situation. The conditions for movements

of $A_i$ and $A_j$ are stated as follows:
If $({}^{A_j}FSP_L \bigcap Base^{A_i} = NULL)$ AND $({}^{A_j}FSP_R \bigcap Base^{A_i} = NULL)$, then $A_j$ can move safely and $A_i$ stops.
If $({}^{A_j}FSP_L \bigcap Base^{A_i} \neq NULL)$ OR $({}^{A_j}FSP_R \bigcap Base^{A_i} \neq NULL)$, then neither $A_j$ nor $A_i$ can move without collision. In this case, either one of these robots needs to turn and move away from the path of the other one. Existing navigation algorithms in literature can be used to bring the displaced robot towards target. As we are interested in traffic scheduling in this work, we derive the following criteria considering deviation of $A_i$ from its current path. The analysis is similar for $A_j$ if it deviates from its path. We present the required minimum turning and displacement as follows:
If $({}^{A_i}FSP_L \bigcap Base^{A_j} = NULL)$ AND $({}^{A_i}FSP_R \bigcap Base^{A_j} \neq NULL)$, then $A_i$ needs to have a minimum left turn $\theta_l$ and displacement $L_l$ defined by

$$L_l = \sqrt{(a_1 - x^i_{1R})^2 + (a_2 - y^i_{1R})^2} \quad (25)$$

$$\theta_l = cos^{-1}\frac{L({}^{A_i}FSP)^2 + L_l^2 - a_3}{2L_l L({}^{A_i}FSP)} \quad (26)$$

where

$$a_1 = x^j_R(k) + \frac{W({}^{A_j}FSP)}{\sqrt{2}}\cos(\phi^j_R(k) + \frac{\pi}{4})$$

$$a_2 = y^j_R(k) + \frac{W({}^{A_j}FSP)}{\sqrt{2}}\sin(\phi^j_R(k) + \frac{\pi}{4})$$

$$a_3 = (a_1 - x^i_{2R})^2 + (a_2 - y^i_{2R})^2$$

If $({}^{A_i}FSP_L \bigcap Base^{A_j} \neq NULL)$ AND $({}^{A_i}FSP_R \bigcap Base^{A_j} = NULL)$, then $A_i$ needs to have a minimum right turn $\theta_r$ and displacement $L_r$ defined by

$$L_r = \sqrt{(a_4 - x^i_{1L})^2 + (a_5 - y^i_{1L})^2} \quad (27)$$

$$\theta_r = cos^{-1}\frac{L({}^{A_i}FSP)^2 + L_r^2 - a_6}{2L_r L({}^{A_i}FSP)} \quad (28)$$

where

$$a_4 = x^j_R(k) + \frac{W({}^{A_j}FSP)}{\sqrt{2}}\cos(\phi^j_R(k) + \frac{3\pi}{4})$$

$$a_5 = y^j_R(k) + \frac{W({}^{A_j}FSP)}{\sqrt{2}}\sin(\phi^j_R(k) + \frac{3\pi}{4})$$

$$a_6 = (a_4 - x^i_{2L})^2 + (a_5 - y^i_{2L})^2$$

If $({}^{A_i}FSP_L \bigcap Base^{A_j} \neq NULL)$ AND $({}^{A_i}FSP_R \bigcap Base^{A_j} \neq NULL)$, then $A_i$ can take either right or left turn as outlined here. During this deviation phase $A_j$ remains stopped.
b) $R^j_{ML} < 0$ AND $R^j_{MR} < 0$
This condition confirms that intersections of left and right limiting FSP of $A_i$ with the line segment of ${}^{A_j}FSP_M$ has happened at the opposite direction of motion of $A_i$ or along the direction of motion of $A_i$ but beyond the length of FSP. So, both $A_i$ and $A_j$ can move safely.

Here, $AND$ and $OR$ represent logical conditions.

## VII. Results

In this section, traffic scheduling for various situations are discussed as per the proposed method. Figures 6 through 8 are considered again for a general discussion.

Condition ($R_R < 0$ AND $R_L < 0$) holds for Figures 6 (i), (viii), Figures 8 (i), (vi). In Fig. 6 (i), both $R_R$ and $R_L$ have negative values. Moreover, $|R_R| > 1$ and $|R_L| > 1$ as the FSP of $A_i$ intersects ${}^{A_j}FSP_M$ externally along $A_j$'s direction of motion. Whereas in Fig. 6 (viii), $|R_R| < 1$ and $|R_L| < 1$ as FSP of $A_i$ intersect ${}^{A_j}FSP_M$ externally in the opposite direction of motion of $A_j$. Similarly, other figures can be explained in light of this proposed method. It is observed that both of these robots can move safely as per the current situation.

Condition $({}^{A_i}FSP_L \bigcap Base^{A_j} = NULL$ AND ${}^{A_i}FSP_R \bigcap Base^{A_j} = NULL)$ along with ($R^j_{ML} > 0$ OR $R^j_{MR} > 0$ ) holds true for various situations as shown in Figures 6 through 8. These conditions hold true for Figures 6 (ii)-(iii), Figures 7 (i)-(vi), Figures 8 (ii)-(iii). It is observed that, in all figures, $R_R$ and $R_L$ have various combinations of values except ($R_R < 0$ AND $R_L < 0$). For example, ($R_R > 0$ and $R_L < 0$) in Fig. 6 (ii), but in Fig. 6 (iii) ($R_R > 0$ and $R_L > 0$) and in Fig. 8 (ii) ($R_R < 0$ and $R_L > 0$). For all these situations, $A_i$ is safe to move further while $A_j$ stops to avoid collision.

The condition $({}^{A_i}FSP_L \bigcap Base^{A_j} \neq NULL$ OR ${}^{A_i}FSP_R \bigcap Base^{A_j} \neq NULL)$ along with ($R^j_{ML} > 0$ OR $R^j_{MR} > 0$) also holds true for various situations. These conditions hold true for Figures 6 (iv)-(vii), Figures 8 (iv)-(v). For all these situations, $A_i$ cannot move further because of possibilities of collision with $A_j$. In these cases also, $R_R$ and $R_L$ have various combinations of values except ($R_R < 0$ AND $R_L < 0$).

### A. *Simulation results*

In this section, we present simulation results. The starting and target positions of $A_i$ and $A_j$ are denoted by 'o' and '*' respectively. The line connecting the initial and target positions of each robot represents the actual path traveled by the robot. Figures 10 through 12 show different situations between these robots. In Figure 10, the traffic condition 1 is valid until the FSPs of these robots overlapped. So, both of them move forward. During the overlapped period, condition 2 a) is valid. So, either $A_i$ or $A_j$ can move in this situation. In this work, priority is given to $A_i$. So, $A_i$ moves while $A_j$ stops for a safe passage of $A_i$. After this period, condition 3 b) is valid for a while when $A_j$ remains at the back side of $A_i$. So, both of them can move safely. Again condition 1 is dominant after this situation allowing both of them to move forward. The initial positions are changed

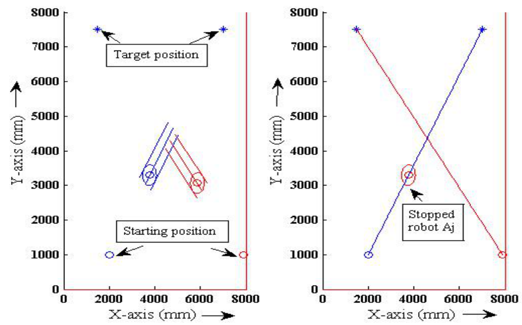


Fig. 10. Traffic scheduling for a pair of robots through communication

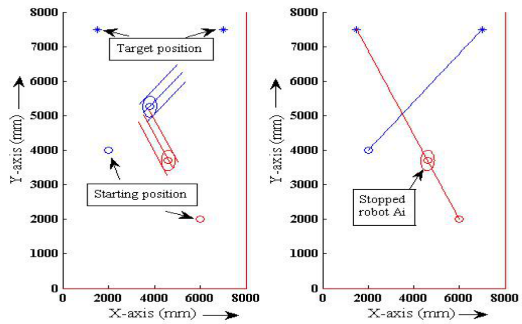


Fig. 11. Traffic scheduling for a pair of robots through communication

for these robots leading to different situations as depicted in Figure 11. The FSP of $A_i$ intersect the base of $A_j$ during movement. So, $A_i$ stops to avoid collision allowing $A_j$ to move further. In the next simulation, the target and initial positions are interchanged for each robot (Figure 12). This results in another set of situations. It is observed that $A_j$ is stopped while $A_i$ continue its forward movement. From these results, it is observed that these robots can maintain a proper traffic schedule and avoid collisions without ranging sensors.

## VIII. Conclusion

We present a multi-robot networking paradigm in this work. This work increases flexibility of deploying multi-robot systems without a need of a centralized control. Here individual robot can take its own decision and/or share information with other robots depending on applications. So resources of information are not restricted to a central location rather shared in distributed manners. In continuation to this shared information paradigm, we present a traffic scheduling method based on the interactions of the FSP limiting lines of mobile robots. We consider robots without ranging sensors. Some basic properties of intersection of line segments are used to develop this knowledge. In this present version of work, a common guideline is presented for movement sequences of a pair of mobile robots and a priority is given to $A_i$ when either $A_i$ or $A_j$ can move in a situation. Simulation results are shown to validate the proposed method. A future work is planned to utilize the developed network paradigm addressing the priority issues while more than two robots share the same environment. This work has several applications in autonomous mobile robotics including factory environment and automatic traffic scheduling at a junction of several roads.

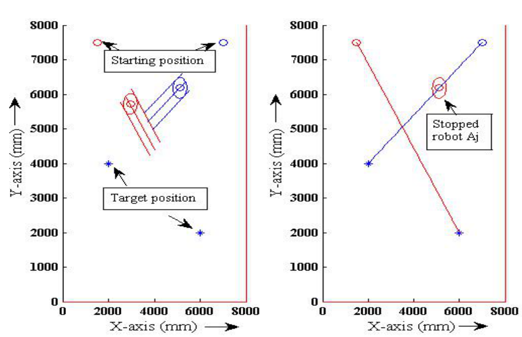


Fig. 12. Traffic scheduling for a pair of robots through communication

## Acknowledgements

Dr. Anjan Kumar Ray is supported by the Centre of Excellence in Intelligent Systems project, funded by the Integrated Development Fund (through its facilitating agent ILEX, and InvestNI.

## References

[1] Y. U. Cao, A. S. Fukunaga, and A. B. Kahng, "Cooperative mobile robotics: Antecedents and directions," *Autonomous Robots*, vol. 4, pp. 1–23, 1997.

[2] A. Teja V, D. V. K. Viswanath, and K. M. Krishna, "A mixed autonomy coordination methodology for multi-robotic traffic control," in *IEEE International Conference on Robotics and Biomimetics*, Bangkok, Thailand, 2009, pp. 1273–1278.

[3] J. G. Bender, "An overview of systems studies of automated highway systems," *IEEE Transactions on Vehicular Technology*, vol. 40, no. 1, pp. 82–99, February 1991.

[4] D. Swaroop and J. K. Hedrick, "Constant spacing strategies for platooning in automated highway systems," *ASME J. Dyna. Syst. Measure. Control,*, vol. 121, pp. 462–470, 1999.

[5] J. Anda, J. LeBrun, D. Ghosal, CN. Chuah, and M Zhang, "Vgrid: Vehicular adhoc networking and computing grid for intelligent traffic control," in *IEEE vehicular technology conference*, 2005, vol. 5, pp. 2905–2909.

[6] S. Biswas, R. Tatchikou, and F. Dion, "Vehicle-to-vehicle wireless communication protocols for enhancing highway traffic safety," *IEEE Communications Magazine*, pp. 74–82, January 2006.

[7] D. Fox, W. Burgard, H. Kruppa, and S. Thrun, *Collaborative multi-robot localization*, Springer, Berlin/Heidelberg, 1999.

[8] L. E. Parker, *Encyclopedia of Complexity and System Science*, chapter Path Planning and Motion Coordination in Multiple Mobile Robot Teams, pp. 1–24, Springer, 2009.

[9] A. K. Ray, L. Behera, and M. Jamshidi, "Sonar-based rover navigation for single or multiple platforms: forward safe path and target switching approach," *IEEE systems journal*, vol. 2, no. 2, pp. 258–272, June 2008.