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A Modified Navigation Technique for Formation Control ofSonar-Equipped Mobile Robots withLarge Obstacle Avoidance

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ABSTRACT:*This paper presents a formation control of multiple mobile robots with large obstacle avoidance. The mobile robots considered in this paper have multiple sonars which are used for not only constructing formation but also avoiding obstacle. The novel modules overcoming the drawbacks of the previous navigation algorithm [12] are introduced to accomplish the obstacle avoidance and formation control. The effectiveness of the proposed techniques are examined by an experiment using three mobile robots.*
KEY WARDS:*Obstacle avoidance, Formation control, Leader-follower method, Sonar assignment*

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I. INTRODUCTION

In recent, formation control of multiple mobile robots has been one of great attentions in robotic society over the past decades because multiple robotic systems contain potentials for accomplishing tasks which are more than single robotic systems can manage; for example, payload/object transportation, exploration, surveillance, search and rescue and mapping of unknown or partially unknown environments. Multiple robots may be required to make a formation for accomplishing those tasks[1] - [8]. The authors have studied the formation control of mobile robots which equip multiple sonars [9]-[12]. The formation control approach adopted in our studies is based on the leader-follower technique [1], [3], [4]. In [9], a distributed control law, called self-made input (SMI), was proposed in the frame of the leader-follower technique. The formation control with an obstacle avoidance was successfully performed by combining the SMI with a reactive collision avoidance method [12]. Since the size of obstacles considered in [12] was almost the same as that of the mobile robots, the time length required for avoiding the obstacle was short; that is, the quantity of avoidance was small. When the size of obstacles is large, the technique used in [12] was not well worked because the amount of avoidance is large. Therefore, further consideration and/or additional techniques are needed.

The aim of this paper is to propose a navigation technique of formation control with a large obstacle avoidance. Based on the technique in the previous study[12],this paper proposes the following modules to overcome the drawbacks in the previous study. First, the shape of the formation is changed to accomplish obstacle avoidance surely. After avoiding the obstacle, the shape of the formation is re-constructed to the original one. Furthermore, some modules are newly introduced to assist the existing modules in the previous navigation algorithm. The effectiveness of the proposed techniques is examined in experiments using three mobile robots.

II. FORMATIONCONTROL AND OBSTACLE AVOIDANCE

This section presents the statements of problemof formation control based on the leader-follower technique, mobile robots used in the experiment and the navigation algorithm in the previous study[12].

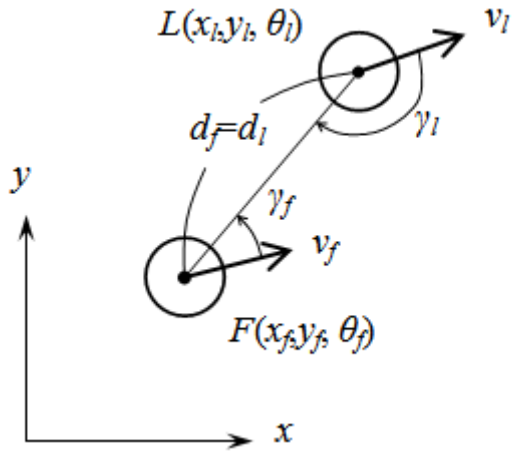


Figure 1: Relative position and relative orientation between leader and follower robots

II.A. Formation Control by Leader-Follower Method

Consider a mobile robot which moves on the two-dimensional plane. The position of the robot is represented by the fixed Cartesian coordinates $(x(t),y(t))$ where t is the continuous-time. The directional angle of the robot is $\theta(t)$ $(-\pi \le \theta(t) < \pi$ [rad]), which is measured from the positive x-axis. The linear and the angular velocities are respectively $v(t)$ and $\omega(t)$ which are the control commands to the mobile robot. The equation of kinematics of the mobile robot is given by

$$\begin{cases} \dot{x}(t) = v(t)\cos\theta(t) \\ \dot{y}(t) = v(t)\sin\theta(t) \\ \dot{\theta}(t) = \omega(t) \end{cases} \quad (1)$$

The magnitudes of the control commands are constrained as

$$|v(t)| \le v_{\max}, \qquad |\omega(t)| \le \omega_{\max} \quad (2)$$

where $v_{\max}$ and $\omega_{\max}$ are the maximum values of $v(t)$ and $\omega(t)$, respectively.

Figure 1 shows a leader-follower formation control of two mobile robots, where *L*is the leader robot while*F*is the follower robot [1], [4]. Hereafter, the subscript l and f in the notations mean the leader and the follower robots, respectively. The equations of both robots are given by Eq. (1) whose variables are replaced to their own state and input variables. The relative distance between the leader and the follower robots is denoted as d_l $(=d_f)$ and the relative angles from their heading are denoted as γ_l and γ_f, respectively. The objective of the formation control by the leader-follower technique is to navigate multiple mobile robots from start to goal with keeping a formation and without colliding any obstacles. In the concrete, the follower robot is controlled by keeping (d_f, γ_f) to their references$(d_f^{ref}, \gamma_f^{ref})$ which are specified in advance. The equations of the relative distance and the relative angle include the states and the control commands with respect to both the leader and the follower robots. To realize the formation control by means of a distributed manner, Fujimori et al. [9] proposed a follower control law, called self-made input (SMI), in which the follower input v_f and ω_f were given by the state of the follower robot and the estimates of the leader robot. The SMI does not need any communication tool between the leader and the follower robot. This paper uses the SMI for the formation control law.

II.B. Mobile Robot Pioneer

Figure 2 shows photos of Pioneer-1 and -2 [13] - [15] which are used for formation control in this study. The size of Pioneer-1, shown in the left and the middle photos, is 450 [mm] from stem to stern, 360 [mm] between the left and right wheels, and 225 [mm] to the top. The size of Pioneer-2, shown in the right photo, is almost the same as that of Pioneer-1. The drive system of Pioneer-1 and -2 is powered by two reversible DC motors. Each drive motor includes an optical encoder for position sensing. Pioneer-1 has seven ultrasonic sonar transducers. The sonars are attached to the front and both sides. While Pioneer-2 has eight ultrasonic sonar transducers. Table I shows the attached angles of the sonars from the forward direction of Pioneer-1 and -2, respectively.

Figure 2: Pioneer-1 and -2

Table I:Attached angles of sonars in Pioneer-1 and -2

No. of sonar	φ_i[deg]	
i	Pioneer-1	Pioneer-2
0	90	90
1	30	50
2	15	30
3	0	10
4	-15	-10
5	-30	-30
6	-90	-50
7	-	-90

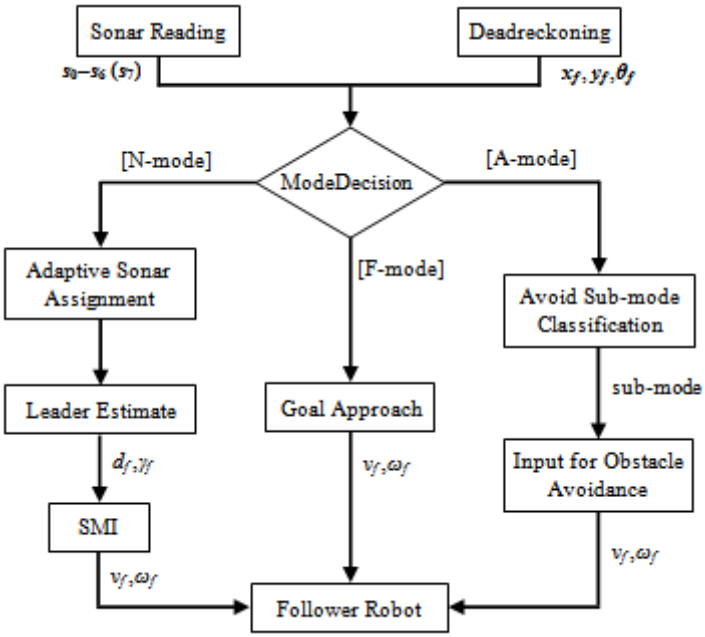


Figure 3: Signal process from sonar reading and deadreckoning to control commands of follower robot presented in [12] (previous navigation algorithm)

The multiple sonars are used not only to detect an obstacle for collision avoidance but also to track the leader robot for constructing formation. Letting s_i be the output of the i-th sonar and φ_i be the attached angle of the i-th sonar, d_f and γ_f are then calculated by averaging the outputs of the fired sonars with the weighting coefficient w_i of the i-th sonar [12]; that is,

$$d_f = \frac{\sum_{i\in F} w_i s_i}{\sum_{i\in F} w_i}, \qquad \gamma_f = \frac{\sum_{i\in F} w_i \varphi_i}{\sum_{i\in F} w_i} \tag{3}$$

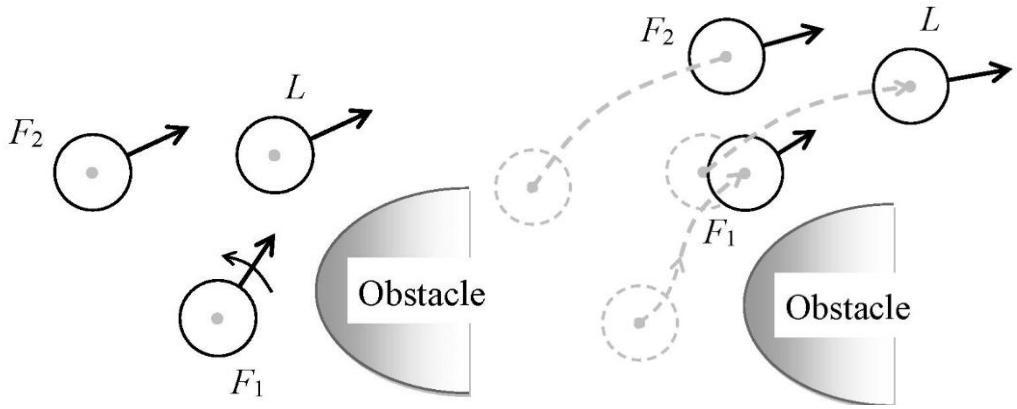
where Φ is the set of the specified sonars number which sonars are used for determining d_f and γ_f. The details are described in [12].

II.C. Obstacle Avoidance

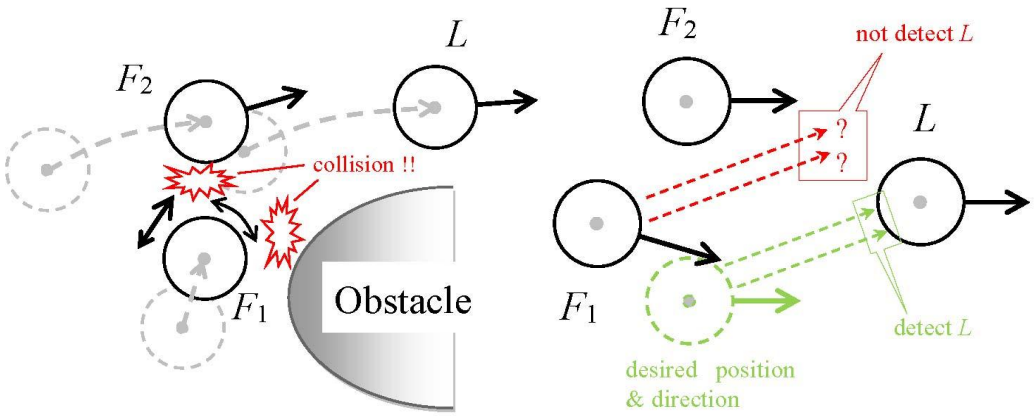
A reactive obstacle avoidance technique which was given in [12] is also used in this study. The process mentioned in [12] summarized as follows. According to the fired sonars which detect an obstacle within the specified range, the obstacle avoidance aspects are classified into eight categories; *Front, Left, Right, Front-Left, Front-Right, Left-Front-Right, Left-Right* and *Back.* These are called the sub-modes in the collision avoidance. The control commands of the follower robot v_f and ω_f are then given according to the sub-modes. Combining the SMI for the formation control with the reactive obstacle avoidance, a flowchart of signal process to generate the control commands of the follower robot (v_f and ω_f) is shown in Fig. 3[12]. Using the outputs of sonars and the deadreckoning information, one of three modes is selected at Mode Decision, where N-mode means the formation control, A-mode means the obstacle avoidance and F-mode is the final navigation in which the mobile robots approach to the goal and their velocities are decreased.

III. CONTROL STRUCTURE FOR LARGE OBSTACLE AVOIDANCE

This section presents a new navigation algorithm of formation control. First, problems when the previous navigation algorithm Fig. 3 is applied to the formation control with large obstacle avoidance are mentioned. Thenew navigation algorithm including novel modules is then proposed to overcome the problems.



(a) At beginning of obstacle avoidance **(b) A case where a free space is found between F_2 and obstacle**



(c) Collision occurs with F_2 and obstacle **(d) F_1 does not detect L in N-mode after avoiding obstacle**

Figure 4: Aspects of formation control with a large obstacle avoidance by navigation algorithm [12]

III.A. Problems in Previous Algorithm

Figure 4 show aspects that three mobile robots avoid an obstacle with keeping a triangle formation where$L$ is the leader robot, andF_1 and F_2 are the follower robots.Figure 4(a) shows an aspect that L almost finishes avoiding the obstacle and F_1 begins to avoid the obstacle by changing its direction to the left. This action may bring a collision with F_2.F_1 is easy to become the so-called "dead-rock" in which any find free spacecannot be found in the front of F_1.As shown in Fig. 4(b), when F_1fortunatelyfinds free space between F_2

and the obstacle, the obstacle avoidance of F_1 is succeeded with keeping the formation. On the other hand, in the case of Fig. 4(c), if F_1 did not find anenough free space in the front, then F_1 does not avoid the obstacle or misses L; that is, the formation control is failed.As another failed case, Fig. 4(d) shows that F_1 is not able to detect Lafter avoiding the obstacle and returning to the original formation. This case is happened that the sonars for tracking the leader robot are not suitably assigned or the positions of the leader are not acceptably estimated.

III.B. Proposed Navigation Algorithm

To overcome the problems mentioned in the previous subsection, Fig.5 shows the flow chart of the proposed navigation algorithm including the new modules. The modules used in Fig. 3 are also included in Fig. 5. On limitation of the space, the descriptions of F-mode are omitted. The following three points are mainly introduced in the proposednavigation algorithm; (i) N-mode is divided into three sub-modes; N-f-mode, N-r-mode and N-s-mode by the judgement *Nav Select*. (ii) *Form Change* is inserted at the beginning of A-mode. (iii) *Sonar Prediction* and *Move Prediction* are added to assist*Adaptive Sonar Assignment* and *Leader Estimate*, respectively.As far as (iii) is concerned, the dashed lines in Fig. 5 means the exchanges of the information whichis updated in each module when the mode is switched. The rest of this subsection explains these new modules in the discrete-time representation. $t_k$means the k-th sampling time where the sampling time is given by T_s.

1) N-s-mode: In the reactive obstacle avoidance method, the mode is decided by the sonar output situation in time.When the mode returns to N-mode from A-mode, there may be the situation that the obstacle avoidance is not accomplished enough. In this case, A-mode is immediately selected again; that is, the follower robot falls into an unstable movement in which A-mode and N-mode are repeated. To avoid this, the previous control commands are maintained whenthe follower robot comes back to N-mode from A-mode in a while. It is managed by *Keep Command*.

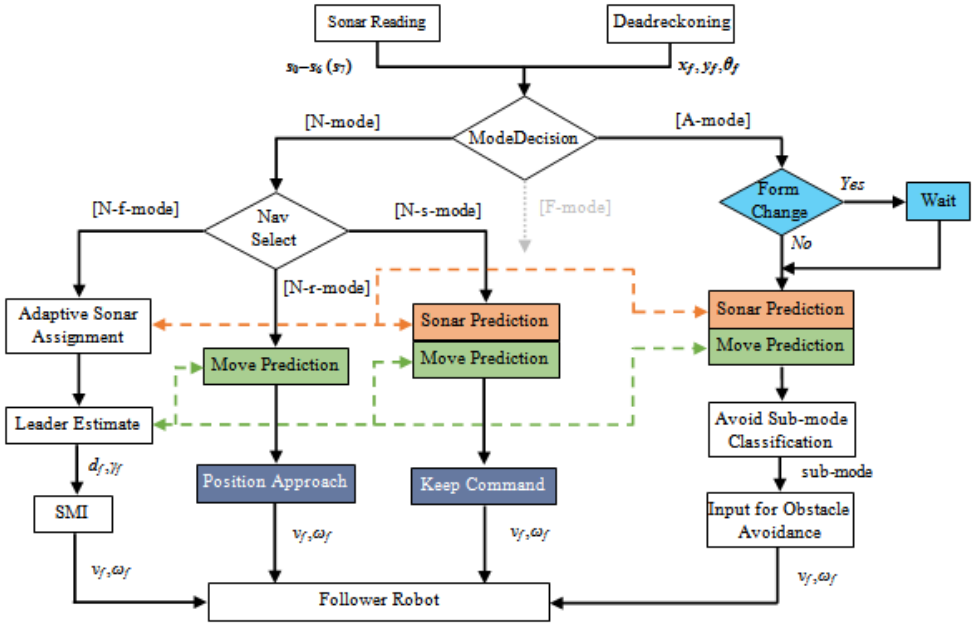


Figure 5: Flow chart of proposed navigation algorithm

2) Form Change:It is necessary for large-sized obstacles that the obstacle avoidance is surely accomplished as the priority. The shape of the formation is then changed to a suitable shape for avoiding the obstacle. In the case of Fig. 4(c), the formation shape of the follower robot F_1 should be changed to aline formation shape; that is, the leader of F_1 is changed to F_2, the references for the new formation shape and the number of the sonars for tracking the leader robot are changed. As another technique, *Wait* module is inserted at the beginning of *Form Change* to avoid the collision with F_2 and obtain an sufficient free space between them. After F_1 waited in a while, F_1 follows F_2 in the line formation shape.

3) Sonar Prediction: After the mode returns from A-mode to N-mode, the sonars for tracking the leader robot may be not suitable because the direction of the follower robot was varied due to the obstacle avoidance behaviors in A-mode.*Sonar Prediction* is then introduced to adjust the number of sonars for tracking the leader robot in A-mode and N-s-mode. Consider a case that the mode is switched to N-s-mode or A-mode at

the discrete-timet_{k1}. Letting $n_u(t_k)$ and $n_l(t_k)$ be the upper and the lower number of the sonars for tracking the leader robot atthe discrete-timet_k, the followings are defined for $k>k_1$:

$$\Delta n(t_k) \equiv n_u(t_k) - n_l(t_k) \tag{4}$$

$$\Delta\theta(t_k) \equiv \theta_f(t_k) - \theta_f(t_{k1-1}) \tag{5}$$

$\Delta n(t_k)$ is the difference of the sonar numbers and $\Delta\theta(t_k)$ is the amount of direction angle change from the mode switch.$n_u(t_k)$ and $n_l(t_k)$ are then shifted by comparing $\Delta\theta(t_k)$ with the attached angle of the sonarsφ_i. The algorithm for Pioneer-1 is shown in the following.

if $(\Delta\theta(t_k) \ge \varphi_2)\ \&\ (\Delta\theta(t_k) < \varphi_1)$, $n_u(t_k) = n_u(t_{k-1}) + 1$
else if $(\Delta\theta(t_k) \ge \varphi_1)\ \&\ (\Delta\theta(t_k) < \varphi_0)$, $n_u(t_k) = n_u(t_{k-1}) + 2$
else if $(\Delta\theta(t_k) \ge \varphi_0)$, $n_u(t_k) = n_u(t_{k-1}) + 3$
$n_l(t_k) = n_u(t_k) - \Delta n(t_k)$
if $(\Delta\theta(t_k) \le \varphi_4)\ \&\ (\Delta\theta(t_k) > \varphi_5)$, $n_l(t_k) = n_l(t_{k-1}) - 1$
else if $(\Delta\theta(t_k) \le \varphi_5)\ \&\ (\Delta\theta(t_k) > \varphi_6)$, $n_l(t_k) = n_l(t_{k-1}) - 2$
else if $(\Delta\theta(t_k) \le \varphi_6)$, $n_l(t_k) = n_l(t_{k-1}) - 3$
$n_u(t_k) = n_l(t_k) + \Delta n(t_k)$

4) Move Prediction:It is important for formation control to catch the position of the leader robot. The position of the leader robot is estimated by using the output of the sonars for tracking leader in *Leader Estimate*. Since *Leader Estimate* is in N-f-mode, the estimation does not perform in other modes. To assist the position estimation, *Move Prediction* is introduced to predict the position of the leader robot in the A-mode, N-s-mode and N-r-mode. It is predicted by supposing that the leader robot moves straight with the normal linear velocity v_0.Consider a case that the mode is switched to N-s-mode, N-r-mode or A-mode at the discrete-timet_{k2}. It was N-f-mode at$t_{k2\text{-}1}$. Then, usingthe estimated position of the leader robot $(\hat{x}_l(t_{k2-1}), \hat{y}_l(t_{k2-1}), \hat{\theta}_l(t_{k2-1}))$, the position of the leader robot for $k>k_2$ is predicted by

$$\begin{cases} \hat{x}_l(t_k) = \hat{x}_l(t_{k-1}) + v_0 T_s \cos\hat{\theta}_l(t_k) \\ \hat{y}_l(t_k) = \hat{y}_l(t_{k-1}) + v_0 T_s \sin\hat{\theta}_l(t_k) \\ \hat{\theta}_l(t_k) = \hat{\theta}_l(t_{k2-1}) \end{cases} \tag{6}$$

5) N-r-mode: After avoiding the obstacle, the follower robot has to re-construct the original formation shape. *Position Approach* in N-r-mode manages the process of the re-construction. First, the target point for constructing the original shape, denoted as P (x_p, y_p), is defined. The follower robot is then controlled so as to move toward the target point. As an example,consider a case that the original formation shape of $F_1$is *Triangle* as shown in Fig. 4(a), while the formation shape for obstacle avoidance is *Line*,and the mode is changed to N-r-mode. Then, the target point of $F_1$is given by

$$\begin{cases} x_p(t_{k3}) = x_{f1}(t_{k3}) + \sqrt{2} d_{f1}(t_{k3}) \cos\{\theta_{f1}(t_{k3}) - \dfrac{\pi}{4}\} \\ y_p(t_{k3}) = y_{f1}(t_{k3}) + \sqrt{2} d_{f1}(t_{k3}) \sin\{\theta_{f1}(t_{k3}) - \dfrac{\pi}{4}\} \end{cases} \tag{7}$$

where $(x_{f1}, y_{f1}, \theta_{f1})$ are the states of F_1 and d_{f1} is the relative distance. Equation (7) means that the target point is given to make a right-angled isosceles triangle with positions of F_1 and F_2 at t_{k3}.It is necessary to updatethe target pointwith progress of the time.Supposing that L moves toward the goal with the normal linear velocityv_0, (x_p, y_p) for$k>k_3$are updated by

$$\begin{cases} x_p(t_k) = x_p(t_{k-1}) + v_0 T_s \cos\theta_p(t_k) \\ y_p(t_k) = y_p(t_{k-1}) + v_0 T_s \sin\theta_p(t_k) \\ \theta_p(t_k) \equiv \tan^{-1} \dfrac{y_g - y_p(t_{k3})}{x_g - x_p(t_{k3})} \end{cases} \tag{8}$$

where (x_g, y_g) are the goal coordinates of L. Furthermore, since the leader of F_1after re-construction is changed to L from F_2, it is necessary that the estimated position of the leader robot is changed as

$$\begin{cases} \hat{x}_l(t_{k3}) = \hat{x}_l(t_{k3-1}) + d_{f1}^{ref} \cos\{\theta_p(t_{k3}) + \gamma_{f1}^{ref}\} \\ \hat{y}_l(t_{k3}) = \hat{y}_l(t_{k3-1}) + d_{f1}^{ref} \sin\{\theta_p(t_{k3}) + \gamma_{f1}^{ref}\} \end{cases} \tag{9}$$

where d_{f1}^{ref} and γ_{f1}^{ref} are the references of the relative distance and the relative angle of F_1, respectively. After F_1 reached near the target point, the mode is changed to N-f-mode from N-r-mode. The re-construction is succeeded if F_1 detected and tracked L again.

IV. EXPERIMENTS OF FORMATION CONTROL

This section presents an experimental result using three mobile robots; two Pioneer-1 and one Pioneer-2, to demonstrate the effectiveness of the proposed navigation techniques. The leader robot is denoted as L, while the two follower robots are denoted as F_1 and F_2also in this section. The formation shape for formation control was given by *Triangle*, while the one for obstacle avoidance was *Line*. Theirreferenced relative distance and angle were given as follows.

- *Triangle* (shape=73)
  d_{f1}^{ref} = 600 [mm], γ_{f1}^{ref}= 15 [deg] for F_1
  d_{f2}^{ref} = 600 [mm], γ_{f2}^{ref}= -30 [deg] for F_2
- Line (shape=71)
  d_{f1}^{ref} = 600 [mm], γ_{f1}^{ref}= 0 [deg] for F_1
  d_{f2}^{ref} = 600 [mm], γ_{f2}^{ref}= 0 [deg] for F_2

The formation velocity and the maximum command inputs were given by v_0 =100 [mm/s],$v_{\max}$ =200 [mm/s] and$\omega_{\max}$ =6[rad/s]. The sampling time was given by T_s=0.1 [s].

The experimental result of the formation control with a large obstacle is shown in Fig. 6 - 10. In Figs. 6 and7, the solid-lines indicate traces of L, F_1 and F_2. The dashed-lines indicate traces of leader position estimated by both F_1 and F_2,respectively. The origin of the Cartesian coordinates was placed at the start point of L. The goal of L was located at (6000, 0) [mm]. The positions of robots were obtained by deadreckoning of the robots. The accumulated error on the positions was less than a few centimeters in the experiment since the travel distance of the robots in the experiment was not so long. F_1 and F_2 were placed to make a triangle at start. The experiment was therefore started with supposing that an object detecting by F_1 and F_2 during a few initial seconds was L. An ellipsoidal obstacle was placed on the way between start and goal. The size was approximately 1300 x 800 [mm]. The upper and the lower of Fig. 8 respectively show the time histories of the flag number and the formation shape of F_1 and F_2 where the mode flag numbers are listed in Table II. Figures 9 and 10 are the relative distance and angle of F_1,where d_{f1}andγ_{f1} were obtained the Eq. (3), and d_{f1}^{*}andγ_{f1}^{*} were true relative distance and the true relative angle.

After L avoided the obstacle, F_1 encountered the obstacle. According to the judgement of *Form Change*, the formation shape of F_1 was changed to *Line* (shape=71) at t=17.2 [s] and its leader robot was changed from L to F_2 (Fig. 8). The locations of L, F_1 and F_2 in this time are marked by the black, blue and red asterisks in Figs. 6 and 7, respectively. The leader position estimated by F_1, drawn by the cyan dashed-line, was shifted to the trace of F_2 as shown in Figs. 6 and 7. At t=40.0 [s], the distance from F_1 to the obstacle was longer than a threshold. Then, the mode of F_1 was selected as N-r-mode (flag=18), the re-construction of the formation shape in F_1 began; that is, t_{k3}=40.0 [s]. The locations of L, F_1 and F_2 at this time are marked by the black, blue and red triangles in Figs. 6 and 7, respectively. The leader robot of F_1 after re-construction was returned to L. Then using Eq. (9), the leader position estimated by F_1 was changed from the position marked by the red-edged cyan triangle ($t_{k3\text{-}1}$=39.9 [s]) to the one marked by the black-edged cyan triangle (t_{k3}=40.0 [s]) in Fig. 6. Comparing the cyan-triangles to the red and the black triangles in Fig. 6, it is seen that these estimated leader positions were properly estimated. The target position of $F_1$for re-constructing the triangle formation shape was calculated by Eq. (7) at the position marked by the green triangle. F_1 then moved the targeted position with the maximum linear velocity. The target positionwas also updated by Eq. (8) toward to the goal with the normal linear velocity. The re-construction was finished at t=49.4 [s]. The locations of L, F_1 and F_2 at this time are marked by the black, blue and red circles in Fig. 6. The original formation shape*Triangle* was re-constructed since F_1detected L again after that. As explained so far, the proposed techniques were effective in the formation control with the large obstacle avoidance.

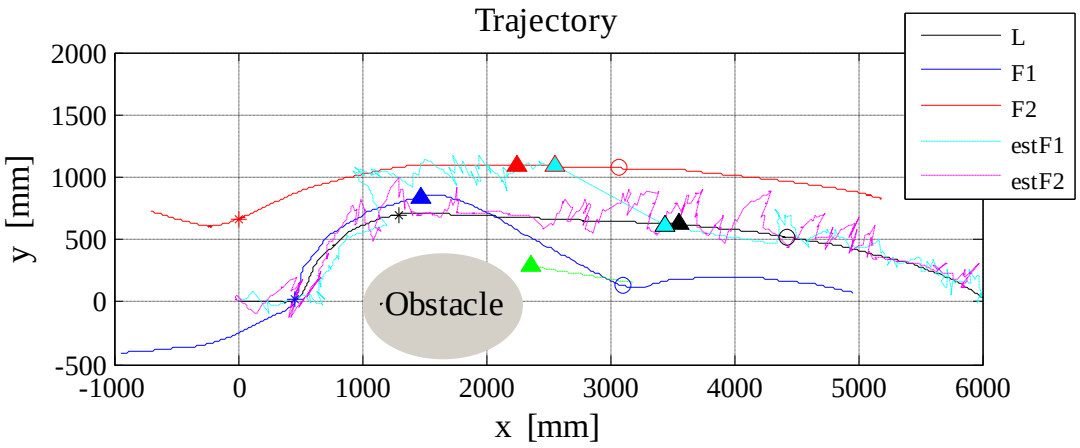


Figure 6: Traces of L, F_1 and F_2 and traces of leader position estimated by L, F_1 and F_2

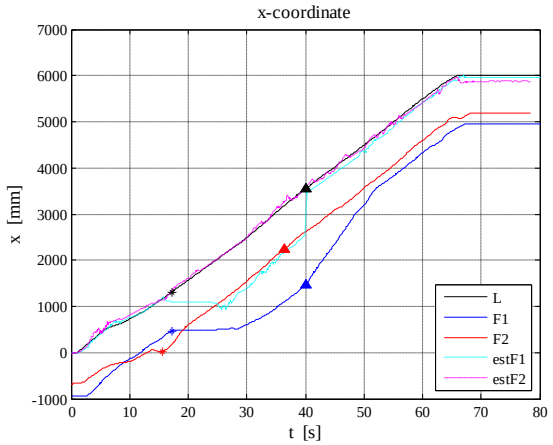


Figure 7: Time histories of x-coordinate; $x_l(t)$, $x_{f1}(t)$, $x_{f2}(t)$ (drawn by solid-lines) and $x\hat{}_l(t)$ (drawn by dashed-lines) estimated by F_1 and F_2

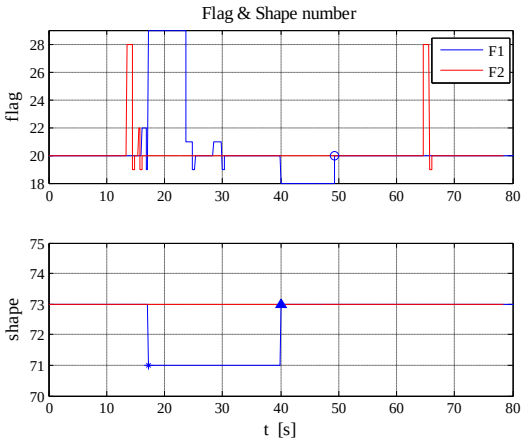


Figure 8: Time histories of mode flag and formation shape

Table II: Flag number and mode

flag number	mode	flag number	mode
18	N-r-mode	24	Left in A-mode
19	N-s-mode	25	Left-Right in A-mode
20	N-f-mode	26	Front-Left in A-mode
21	Right in A-mode	27	Left-Front-Right in A-mode
22	Front in A-mode	28	Back in A-mode
23	Front-Right in A-mode		

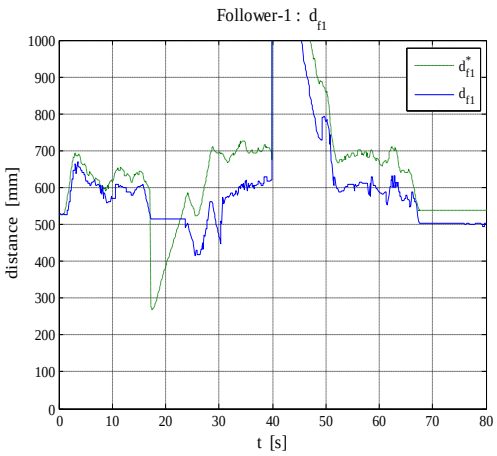


Figure 9: Time histories of relative distance d_{f1}

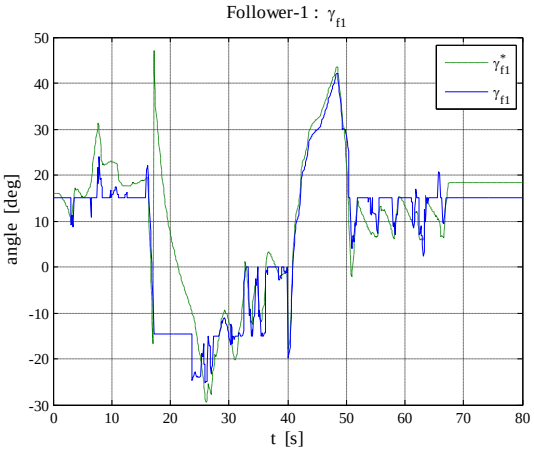


Figure 10: Time histories of relative angle γ_{f1}

V. CONCLUDING REMARKS

This paper has presented a formation control of multiple mobile robots with large obstacle avoidance. The mobile robots considered in this paper had multiple sonars which were used for not only constructing formation but also avoiding obstacle. Based on the techniques [12], some novel modules were introduced to accomplish the obstacle avoidance and formation control. The effectiveness of the proposed techniques wasexamined by an experiment using three mobile robots.

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