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Distributed Formation Control using Consensus for Multiple Humanoid Robots

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Abstract—Formation control in multi-robot is one of the problems widely studied and variety of methods have been developed with their own advantages and disadvantages. Distributed control has the advantage in that it does not require centralized coordination, allowing rapid restructuring in the event of failure of one of the agents. Another advantages include saving computation power, amount of data transmitted over communication, and immunity to delay. In this research a distributed formation controller is designed and implemented in humanoid robots. The distributed controller is designed consisting of layer for tracking, layer for constructing the formation, and consensus layer that keeps the error between each agent can be agreed upon so that a reference can be achieved together. To solve the problem of bad odometry suffered by legged mobile robot caused by the slip between the legs with a floor, visual odometry is employed using the ceiling camera. The control system is simulated using GNU-Octave software and implemented on humanoid robots NAO from Aldebaran. Experiment demonstrates that the distributed controllers are able to closely follow the desired reference.

Keywords—Consensus, formation control, humanoid robot, communication topology.

I. Introduction

Robot has been a used in research for a long time. It is now around us as production tools, used when it is too dangerous for man, or when precision and high repeatability are needed.

Nowadays, one of the active research areas within mobile robot is solving control problems in multiple robots environment. These include path planning research for multi robot [4], obstacle avoidance [2], formation forming and keeping [1, 5], flocking and foraging [3], etc. In reference [5] the authors addressed distributed control problem using consensus algorithm.

In the present paper, consensus algorithm is employed to design distributed control system to form and keep the formation in robot. While previous works in formation control applications employed wheeled mobile robots, in the present study humanoid bipedal robots are employed. The robot humanoid employed as the platform for the formation control experiment is NAO from Aldebaran Robotics. Since humanoid bipedal robot is used, one important issue we encounter while trying to simulate formation control problem is modeling the robot. In most of the works on formation control every agent is modeled by single-integrator. In our experimental platform, if we model the robot using single-integrator, it will produce unnatural movement of the humanoid robot. To overcome this problem, control input saturation is included within the model.

Another issue we encounter is that after one attempt of experiment, it appears that localization of un-wheeled of mobile robot, such as NAO is inaccurate, as proved in [6] and [7], which compared ground position truth with built-in NAO localization. An improvement to localization of NAO was proposed using built-in camera. Then we solved this problem by adding a ceiling camera as visual localization module.

This paper is organized as follows. In Section II, architecture of distributed formation control is presented. In Section III, the discrete-time single integrator model of humanoid in inertial frame is described and simulation result based on the architecture and its model is presented. In Section IV, experimental result is presented to verify effectiveness of the implemented consensus algorithm, along with the use of *visual odometry*. Conclusion is drawn in Section V.

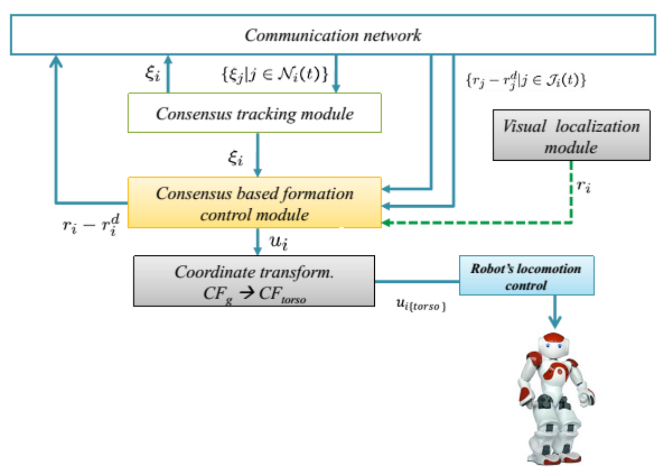

Figure 1 Architecture of distributed formation control

II. Architecture Distributed Formation Control

In this section, we present distributed control architecture for formation control. The architecture is adopted from [1] and consists of three layers: consensus tracking module,

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consensus-based formation control module #i, and robot humanoid #i. Since visual odometry is employed using ceiling camera and we did not use built-in odometry from the humanoid robot, state of every robot is obtained from calculation of *visual odometry*. This architecture can be seen in **Figure 1**.

It is well known that consensus algorithm achieves consensus condition if there is exists spanning tree in the corresponding graph [1]. This requires certain information exchange between agents. The information exchange is carried-out via wireless network formed by wireless access point. Information is then sent to agent(s) based on adjacency matrix. Communication topology used in this formation control experiment is depicted in **Figure 2** below.

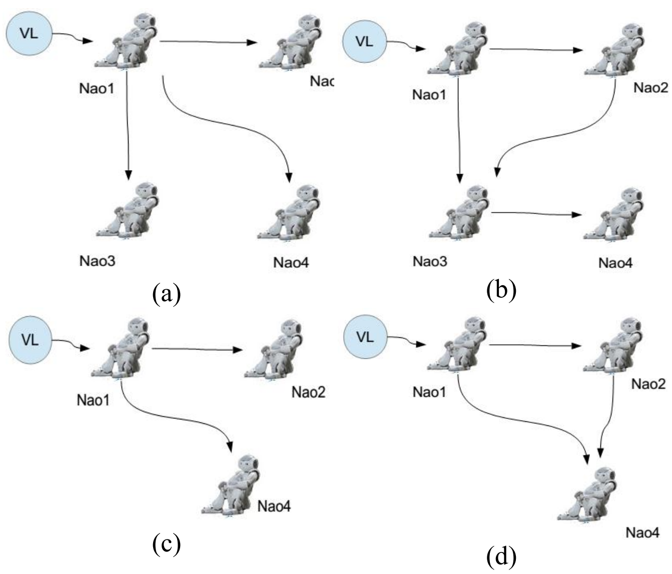

Figure 2 Communication topology implemented in experiment

In the subsequent discussion, we refer **Figure 2(a)** as topology 1, **Figure 2(b)** as topology 2, **Figure 2(c)** as topology 3, **Figure 2(d)** as topology 4. Formation scheme for simulation and experiment is depicted in **Figure 3** with 4 robots and **Figure 4** with 3 robots.

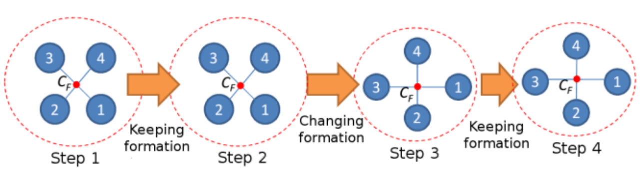

Figure 3 Formation changing steps for 4 robots.

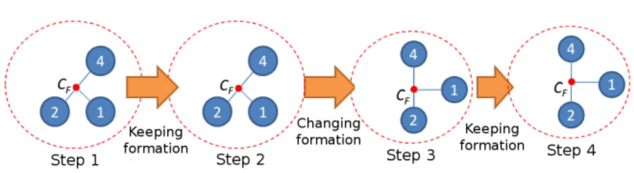

Figure 4 Formation changing steps for 3 robots.

Following [1] communication topology between agent is modelled by directed graph

$$G_{n+1}^{c} \stackrel{\text{def}}{=} (V_{n+1}^{c}, E_{n+1}^{c}) \quad (1)$$

where V_{n+1}^{c} is node set, E_{n+1}^{c} is edge set, adjacency matrix from G_{n+1}^{c} is A_{n+1}^{c} with dimension $(n+1)\times(n+1)$

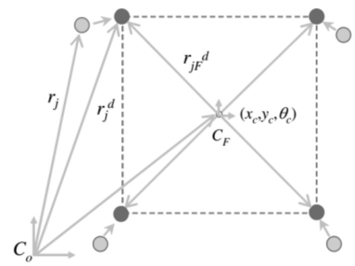

Figure 5 Virtual coordinate and inertial coordinate frames

To form a formation, we used a virtual structure towards a virtual centre. As depicted in **Figure 5** C_F is a virtual coordinate frame located at the centre of virtual structure (x_c, y_c) with orientation θ_c relative to C_O, an inertial coordinate frame. In **Figure 5** $r_j = [x_j, y_j]^T$ represents actual position and $r_j^d = [x_j^d, y_j^d]^T$ represents desired position of robot j. $r_{jF}^d = [x_{jF}^d, y_{jF}^d]^T$ represents translation desired relative to frame C_F for robot j to form the desired formation. To calculate $r_j^d = [x_j^d, y_j^d]^T$ from C_F we use Equation (2):

$$\begin{bmatrix} x_j^d(t) \\ y_j^d(t) \end{bmatrix} = \begin{bmatrix} x_c(t) \\ y_c(t) \end{bmatrix} + \begin{bmatrix} \cos[\theta_c(t)] & -\sin[\theta_c(t)] \\ \sin[\theta_c(t)] & \cos[\theta_c(t)] \end{bmatrix} + \begin{bmatrix} x_{jF}^d(t) \\ y_{jF}^d(t) \end{bmatrix} \quad (2)$$

As mentioned before our consensus tracking module is depicted in **Figure 1**, where $N_i(t)$ and $J_i(t)$ denote, respectively, the set of robot whose instantiations of the coordination variable and position tracking errors are available to robot *i* at time *t*. Tracking consensus module is aimed to lead coordinate state ξ_i to reference variable $\xi^r = [x_c^r, y_c^r, \theta_c^r]^T$, for every agent, and therefore it can follow virtual leader (VL). According to [1] agent (*n+1*) serves as virtual leader for group of agents. This module is described by Equation (3) [1]. In this equation $a_{ij}^c, i = 1, \dots, n,\ j = 1, \dots, (n+1)$ is element (i, j) from adjacency matrix A_{n+1}^c where $A_{n+1}^c \in \Re^{(n+1)\times(n+1)}$ at time t, γ is a scalar positive value, and $\eta_i(t) \stackrel{\text{def}}{=} \sum_{j=1}^{n+1} a_{ij}^c(t)$. In the present study, ξ_i value is obtained from visual odometry, VO system.

$$u_i = \frac{1}{\eta_i(t)} \sum_{j=1}^{n} a_{ij}^c(t)[\dot{\xi}_j - \gamma(\xi_i - \xi_j)] + \frac{1}{\eta_i(t)} a_{i(n+1)}^c(t)[\dot{\xi}^r - \gamma(\xi_i - \xi^r)] \quad i = 1, \dots, n \quad (3)$$

Kinematics of robot movement is modelled as single-integrator with $\dot{r}_i = u_i, i = 1, \dots, n$ where $r_i \epsilon \Re^m$ and $u_i \epsilon \Re^m$ is state variable and input control for robot-i. The detailed and discretised model is shown in Section III. At lower level of consensus tracking module, we apply consensus algorithm as shown in Equation (4). This module follows algorithm proposed in [1] that improves group robustness and reduce formation maintenance error.

$$u_x = \dot{r}_i^d - \alpha_i(r_i - r_i^d) - \sum_{j=1}^{n} a_{ij}^v [(r_i - r_i^d) - (r_j - r_j^d)] \tag{4}$$

Consensus tracking module yields control input represented in global coordinate frame. The issue in this step is that the robot used its coordinate frame system. A module to transform coordinate system from global coordinate frame to robot's coordinate frame is needed. Frame coordinate transformation process usually transform both rotation and translation. However, for this research, we only need to transform the rotation part of control input, that yield by previous module. The transformation from global coordinate frame to robot's coordinate frame is illustrated in **Figure 6**.

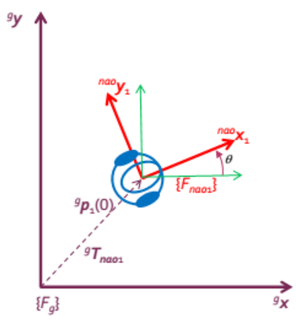

Figure 6 Coordinate frame transformation.

The coordinate frame transformation is given as:

$${}^{nao}u = \begin{bmatrix} cos^g\theta & -sin^g\theta \\ sin^g\theta & cos^g\theta \end{bmatrix} {}^g u \tag{5}$$

III. MODELING AND SIMULATION

In this section, we present model of humanoid robot, control, and simulation results. We assume that the robot is modeled as a discrete integrator consisting of position x, y, and orientation (θ) as seen in Equation (6). This model is derived from NAO API setfootsteps that has input parameter. Equation (6) can be split as in Equation (7) and represented as matrix form in Equation (8).

$$\begin{bmatrix} x_i(k+1) \\ y_i(k+1) \\ \theta_i(k+1) \end{bmatrix} = \begin{bmatrix} x_i(k) + \Delta x_i \\ y_i(k) + \Delta y_i \\ \theta_i(k) + \arctan\left(\frac{\Delta y_i}{\Delta X_i}\right) \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} x_i(k+1) \\ y_i(k+1) \\ \theta_i(k+1) \end{bmatrix} \begin{bmatrix} x_i(k) \\ y_i(k) \\ \theta_i(k) \end{bmatrix} + \begin{bmatrix} \Delta x_i \\ \Delta y_i \\ arctan\left(\frac{\Delta y_i}{\Delta x_i}\right) \end{bmatrix} \tag{7}$$

$$r_i(k+1) = r_i(k) + u_i(k) \tag{8}$$

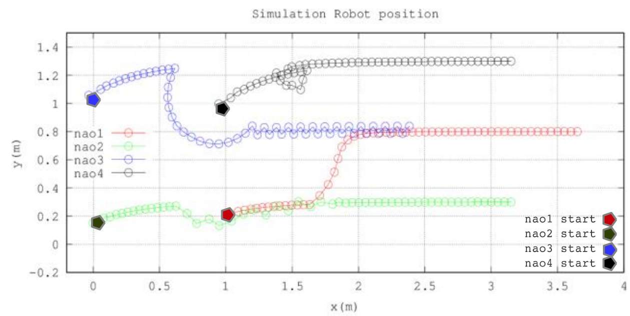

Figure 7 Simulation of keeping-changing-keeping formation with 4 robots and communication topology 1

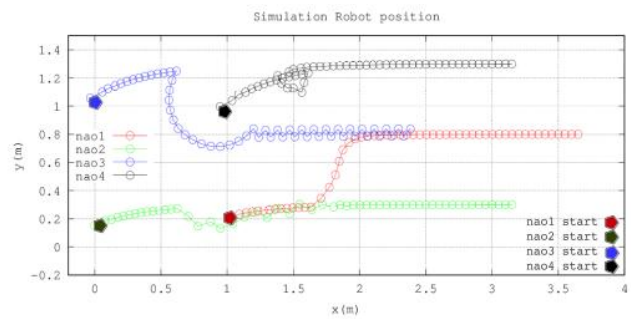

Figure 8 Simulation of keeping-changing-keeping formation with 4 robots and communication topology 2

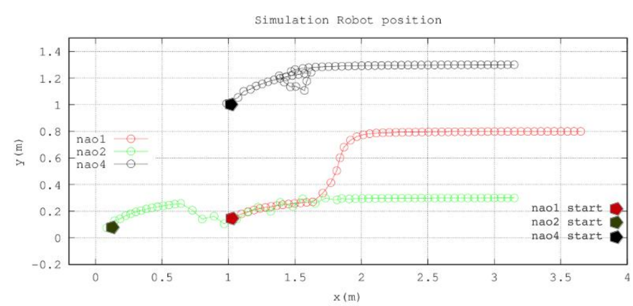

Figure 9 Simulation of keeping-changing-keeping formation with 3 robots and communication topology 3

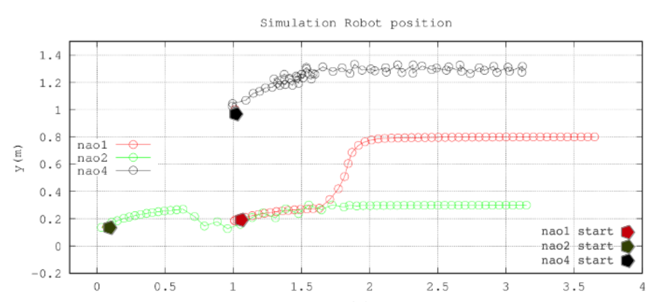

Figure 10 Simulation of keeping-changing-keeping formation with 3 robots and communication topology 4

Consensus control algorithm (4) is then applied. Simulation results for topology 1, 2, 3, 4 are shown in **Figures 7**, **8**, **9**, **10** respectively. As can be seen the agent are put to deviate a little from its desired position from their keeping formation. Therefore, before the group entering its changing formation phase they try to approach its specified formation and keep it. Then when the group entering its changing formation every agent try to alter each position in the new formation and keep their new position and formation for the rest of the experiment.

IV. Experimental Results

In this section we present experiment result on formation control of Nao humanoid robots. The experiment setup consists of humanoid robot, laptop, wireless router, and ceiling camera. Since NAO internal odometry system cannot give an accurate data comparing to the ground truth, we use visual localization. Localization is performed using a ceiling camera and computer laptop as an image processor to recognize the color mark on every NAO head. As can be seen in **Figure 17**, mark for NAO respectively colored as red, green, blue, and yellow. Since we use ceiling camera as localization tools, this caused limited experiment field to camera view coverage. The experimental field is limited at about 4 by 2 meter.

Initial state $x(0)$ for every NAO respectively is a position (1,0), (0,0), (0,1) and (1,1). Thanks to visual odometry we do not actually have to put every robot on exact position, since the mechanism of visual odometry allows the ground position truth as initial state.

It can be seen in **Figure 11** that formation can be kept and changed and then kept again for the rest of experiment. Even if the initial state is not strictly determined, the designed controller can achieve desired formation and changing its formation as required. Based on experiment data, we can calculate error of the resulting states as compared to reference agent. **Figure 15** showed error comparison for experiment shown in **Figure 11**, and **Figure 16** showed error comparison for experiment shown in **Figure 12**.

V. Concluding Remarks

In this study, design and implementation of distributed formation control for multiple robot humanoids using visual localization based on consensus algorithm has been shown to achieve consensus states. The reference trajectory is only known by virtual agent and only one real agent get information. Nevertheless, formation and trajectory can be kept, and formation changing is achieved. Discrepancy between experiment results and simulation in GNU-Octave is mostly caused by the fact that robot model simulated in GNU-Octave was represented as discrete single integrator with saturation, and partly because slip between leg and floor. Reference trajectory is still followed with error varying 0-0.2 m (mostly less than 0.2 m).

A couple of experiments with keeping and changing humanoid formation were performed: 1) Two experiments with 4 agents use communication topology 1 and 2. In experiment with topology 1, it can be seen that the steady state error is less than 0.2 m. In experiment using topology 2, it can be seen that agent 3 which get information from agent 1 and 2 has higher steady state error ranging from 0.2 to 0.4m, while agent 4, getting information only from agent 3, has quite same steady state error as that of agent 3; 2) Two experiments with 3 agents were performed using communication topology 3 and 4. In experiment which used topology 3, it can be seen that steady state error is lower than 0.2 m. In experiment which used topology 4, it can be seen that agent 4 which get information from agents 1 and 2 has higher steady state error of around 0.2-0.4m, as observed in previous experiment. Finally, using visual odometry based on ceiling camera, odometry inaccuracy problem caused by slip between robot leg and floor was solved.

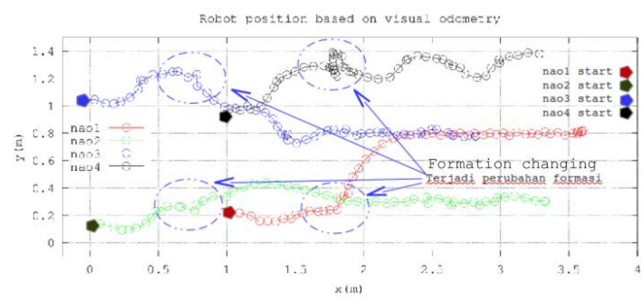

Figure 11 Experiment results of keeping-changing-keeping formation with 4 robots and comunication topology 1

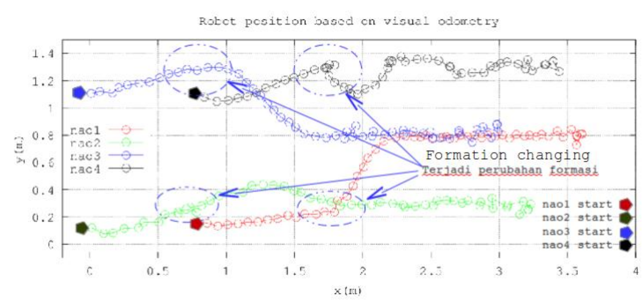

Figure 12 Experiment results of keeping-changing-keeping formation with 4 robots and comunication topology 2

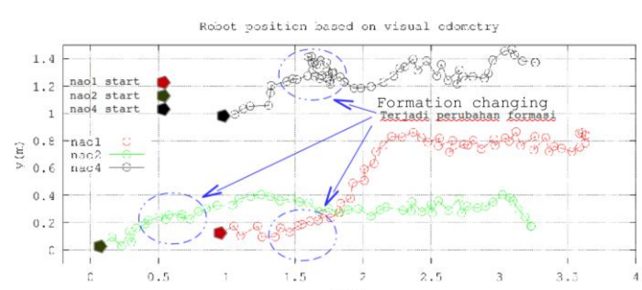

Figure 13 Experiment results of keeping-changing-keeping formation with 3 robots and comunication topology 3

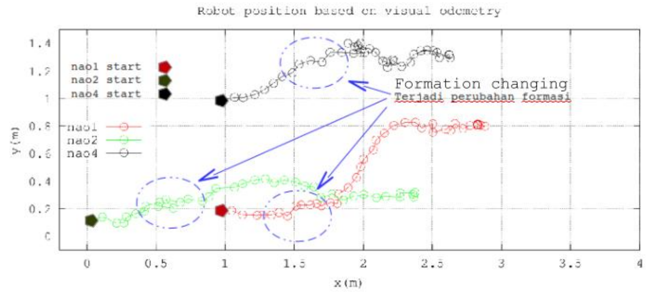

Figure 14 Experiment results of keeping-changing-keeping formation with 3 robots and comunication topology 4

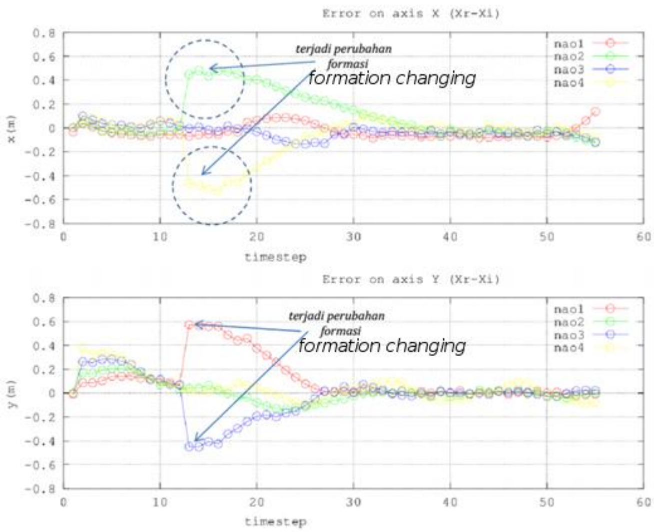

Figure 15 Error performance in experiment with comunication topology 1

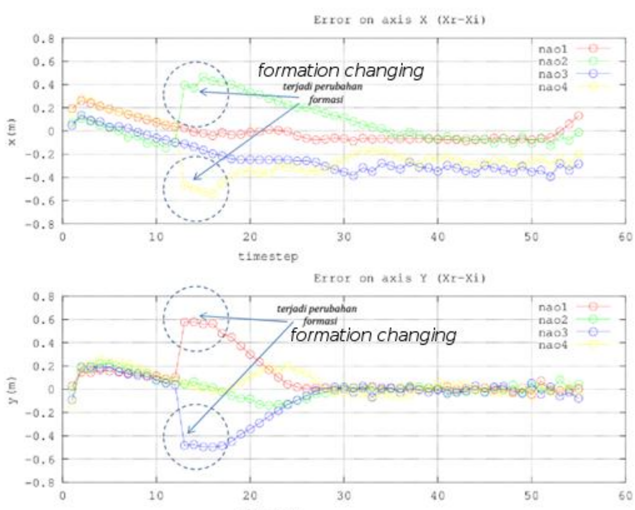

Figure 16 Error performance in experiment with comunication topology 2

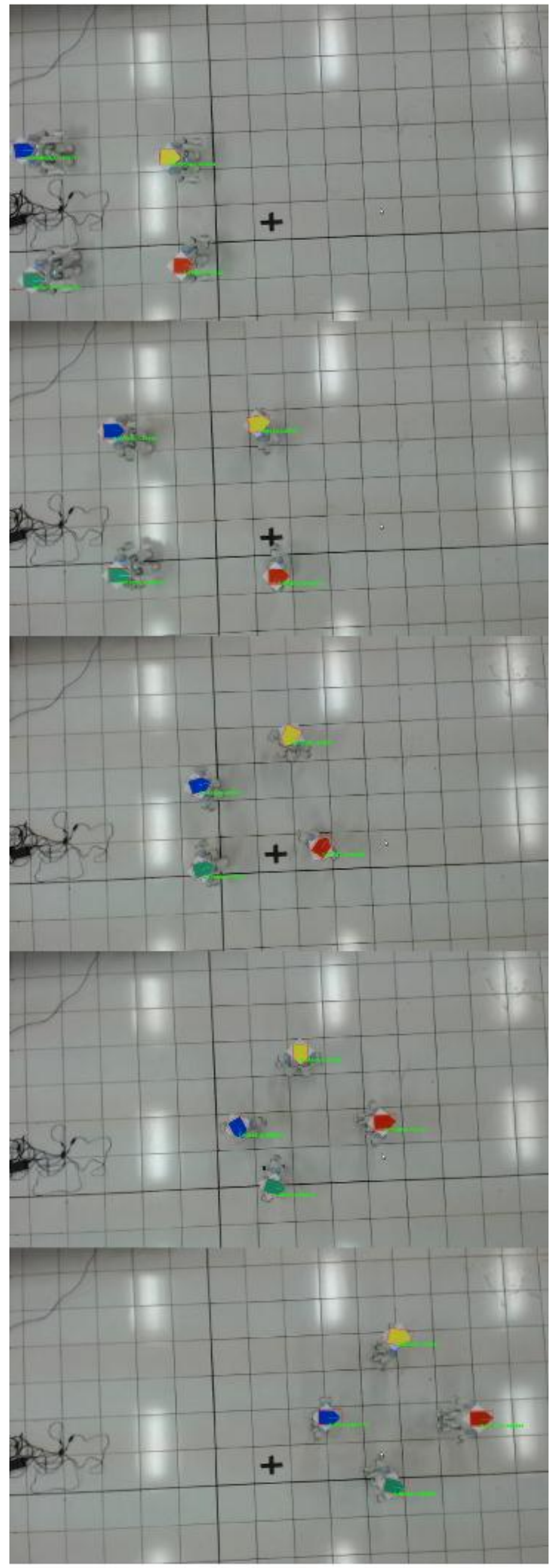

Figure 17 Humanoid formation experiment results viewed from visual localization camera

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