# DISTRIBUTED MOBILE ROBOTS

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The aim of this work is to develop a team of mobile robots that are linked mechanically to each other by a system of physical links and rotary sensors. They sense the rotation and motion of neighbouring robots and move in response to preserve the collective desired configuration of the robots. Only one robot in the team is given rotation and translation instructions. The others simply follow this robot by sensing its motion using the sensors comprising of the links and rotary transducers. The sensors are used to preserve the collective desired configuration despite errors in the motion due to non-identical dynamics and control systems of individual robots. In this paper we investigate one possible arrangement of links and sensors to control the situation described above and present the initial simulation results of motion trajectories obtained for the distributed robots arranged in vertical and horizontal serial-link chains.

## 1. Introduction

The purpose of this work is to develop a group of mobile robots that can be linked to each other with physical links and rotational joints. The links and rotary sensors measure the distance between adjacent robots and measure the angles made by each robot as they rotate with respect to the links and the other robots. The sensing system on each robot senses the motion and rotations of neighbouring robots and copies their motion, see figure 1.

We investigate the use of the sensing system to preserve the collective desired configuration despite errors in the motion due to non-identical dynamics and control systems of individual robots. This type of a collective distributed robot would be useful in many industrial Non-destructive Testing (NDT) inspection tasks that could be performed by a team of small mobile robots that cooperate to perform the inspection faster and more flexibly than large multi-axis scanning arms. An example of an industrial application of a collective system of distributed mobile robots is to perform NDT inspection of large steel plates [1].

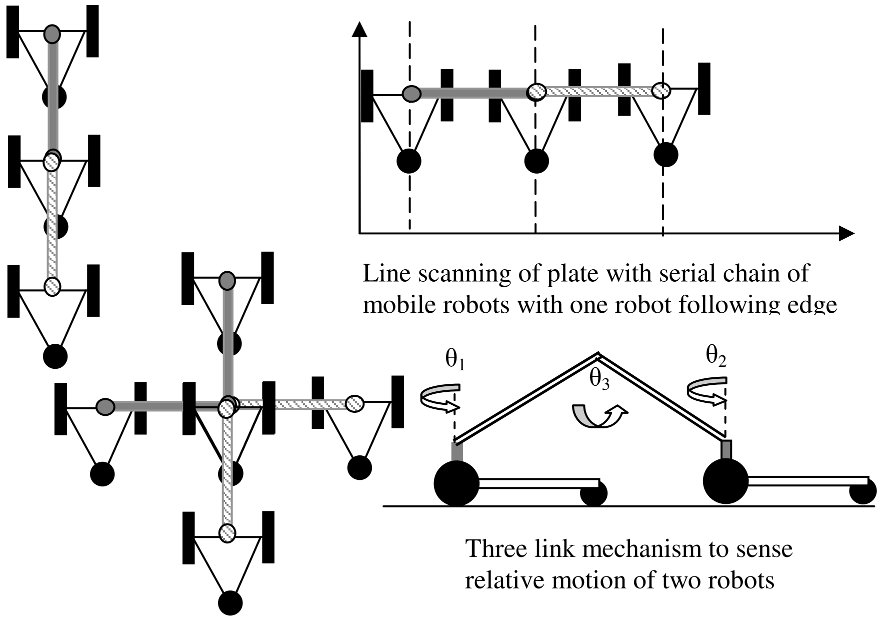


Figure 1. Mobile robots interconnected with a three-link mechanism to sense distance and rotation of neighbouring robots and relative motion.

## 2. Literature Review

Attempts at creating a group of robots which work collectively by considering a mobile robot as an agent, have been studied as a multi agent system [2]. An agent is a robot with just one wheel and proximity sensors, connections of these agents with a mechanical link creates a multi agent system. Each agent can select its own velocity which enables the whole system to either go straight, turn left or right. In [3] simulations are performed of a lattice of robotic elements in different patterns with simple kinematics and dynamics describing each element. Equations are used to model formations of the elements, modifying some variables in these equations allows the elements to rearrange in a different formation. The SWARM-BOT project is also investigating swarming robots which have the ability to self-assemble [4-7]. Pattern formation using simulated robots is explored in [6]. The problem of how a group of connected robots forming a linear structure can move as fast as possible is addressed in [5]. The authors solve the problem by providing each of the robots with a 'traction sensor' "which detects the direction and the intensity of the traction that the turret exerts on the chassis of each robot and by evolving their neural controllers". In [6] the goal is to use a light source as a target for the evolved simulated robots with identical controllers displaying primitive forms of 'situated specialization'.

## 3. Robot kinematics

Figure 2 shows two connected robots. Each robot has two actively driven wheels actuated by two independently controlled motors. The other wheels are passive omni-wheels. A link, that changes length as the robots move away or towards each other, connects the centers of rotation of each robot. The link is attached to the two robots via revolute joints. The robot local coordinate frame {R} is attached to the robot with its origin at the centre of rotation such that the robot rotates around the z-axis.

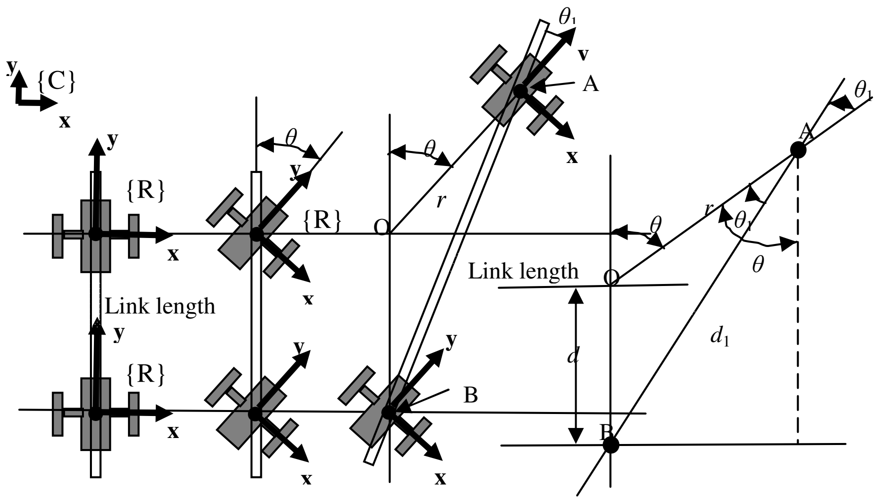


Figure 2. Two robots arranged in a vertical link

The y-axis of this frame is the direction in which translation motion of the robot takes place. The y-axis aligned with the link represents the home position (zero degree angle). The coordinate frame of the collection of distributed robots {C} is aligned to this home position. The required distance between the centers of rotation of the two differentially actuated robots is *d*. The robots change direction with the leader robot first rotating around the z-axis of the frame {C} by angle $\theta$ (in figure 3 this is shown as a negative angle of around 45°). At each sampling instant, the second robot uses the measured angle $\theta$ of the first robot to rotate by this amount. When both robots have finished this rotation motion, the

lead robot translates in the y-axis of its local frame {R} by an amount $r$. The link length changes to $d_1$ and the measured angle to $\theta_1$. If the second robot travels a distance equal to $r$ in the direction of its y-axis then the link length will be adjusted so that $d_1 = d$ and $\theta_1 = \theta$.
The problem is to move the second robot by a distance $r$ using the measured angle $\theta_1$ and the measured distance $d_1$. The rotation angle $\theta$ is also known.

Kinematics equations can be setup to calculate $r$ at each sampling instant to provide a reference position to the discrete-time control system of the follower robot. To align the frame A with frame B, we can take the path AOB or AB.
The equation can be ill conditioned and is not robust.
Horizontal chain of robots: Figure 3 shows a two robot link-up. Robot 1 rotates by angle θ around z-axis. Robot 2 follows this rotation. Robot 1 then moves a distance r in the positive direction of its y-axis. The link between the two robots moves to a new position – link length changes from $d$ to $d_1$ and the angle between the link and robot 2 changes from $\theta$ to $\theta_1$. Robot 2 computes the distance to move along its y-axis to follow the first robot. Again, the equations have singular points and are ill conditioned.

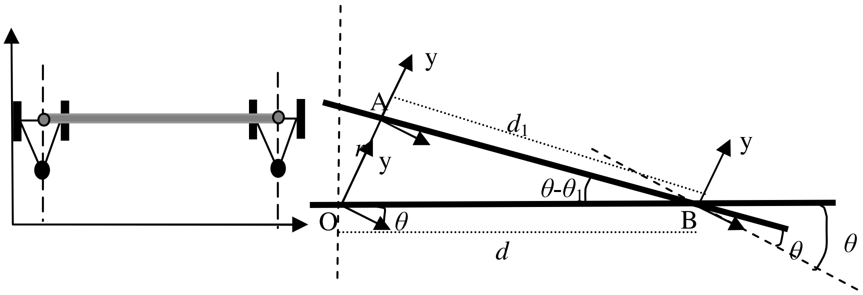


Figure 3. Two robots arranged in a horizontal link-up

## 4. Feedback Control

The approach that we have taken is to use feedback control to decide how to perform the translational motion. To change robot direction, the measured angle $\theta$ of rotation of the leader is used by the following robot's control system as a demand signal and it follows it. After a delay to allow the train of robots to complete their rotation, the lead robot moves in the y-direction of its local coordinate frame. The resulting change of angle $\theta_1$ with respect to the link is used to create an error $e = \theta - \theta_1$. This error is fed back to the following robot via a simple PID controller and its control output applied to the robot to actuate translation motion. Similarly, the angle $\theta_1$ between the third robot and the second is used to control motion of the third robot. Figure 4 shows the control scheme and simulation strategy.

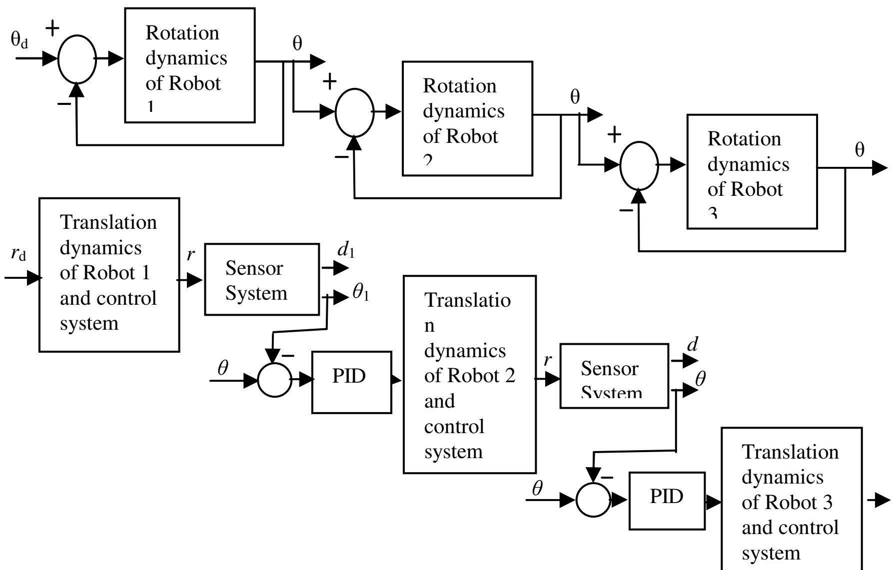


Figure 4. Schematic of the control system that enables robots to follow the leader

## 5. Simulation Results

Results of a simulation study are reported here to see how three robots connected in a serial vertical chain (extreme left in figure 1) could be made to follow a leader by using the angle of rotation of the leader as a reference input at each sampling instant to the next robot in the chain.

A sequence of demanded rotation angles are applied to the control system of the "leader" robot as step inputs. The robots start in the zero degree position. A step demand of -60˚ is made after sixty seconds. This is followed sixty seconds later by a step demand of -90˚, then -120˚, then -90˚, and finally -60˚. The dynamic response of the first robot is shown in figure 5. The measured angle at each sampling instant is sent as a reference signal to the control system of the next robot and its response in turn is sent to the third robot in the chain. This causes the responses to be delayed before all robots are orientated in the same direction. Figure 5 shows these responses. The command to move in the y-direction is given when the robots are in the steady state. A unit step up/down (pulse) position demand is applied. The resulting position trajectory of the leader is shown in figure 5 (dotted curve).

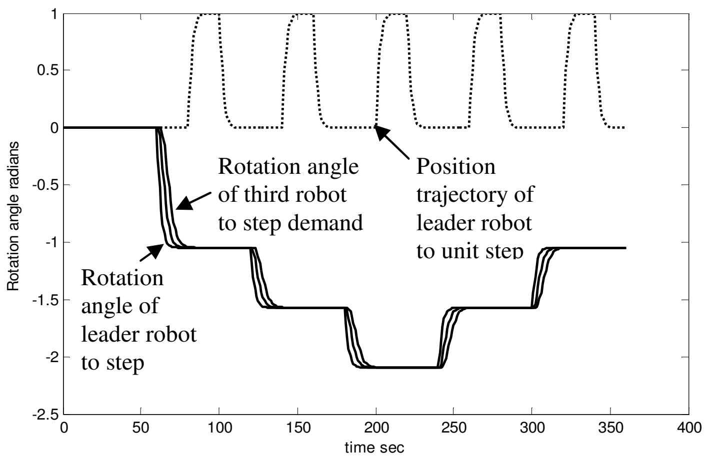


Figure 5. Demanded rotation of the leader robot and rotation trajectories of three robots arranged in a serial link

Applying the control scheme shown in figure 4 is successful. The four graphs in figure 6 show the control system applying the correct translation to the other two robots to enable them to correctly follow the leader and also when the system has motion errors due to unequal dynamics and controller steady state errors. The control system uses the link angle errors (Top left) to compute the control to apply to robots 2 and 3. The resulting position trajectory of the three robots is shown (top right). These result in the World x-y spatial trajectories (Bottom left) and (Bottom right).

Figure 7 shows the control system correcting trajectory errors when the dynamics of the three robots are different. Local control systems of the two following robots produce trajectory errors even with the same inputs (Top Left). These are corrected by the feedback controller (Bottom right) by obtaining the motion trajectory (Top right).

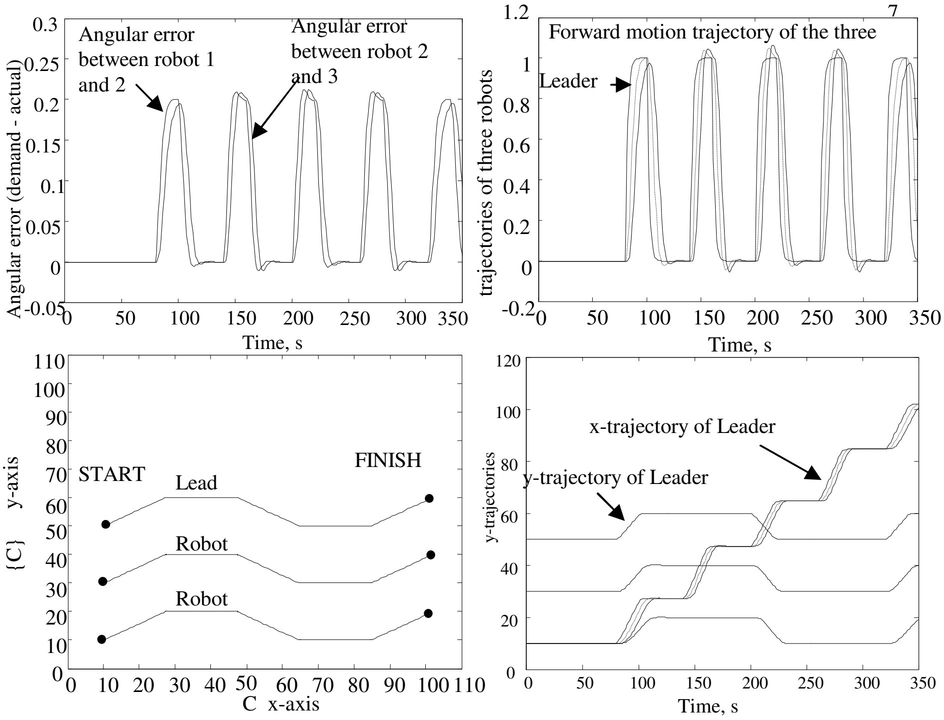


Figure 6. Equal rotational and translational dynamics of all three robots.

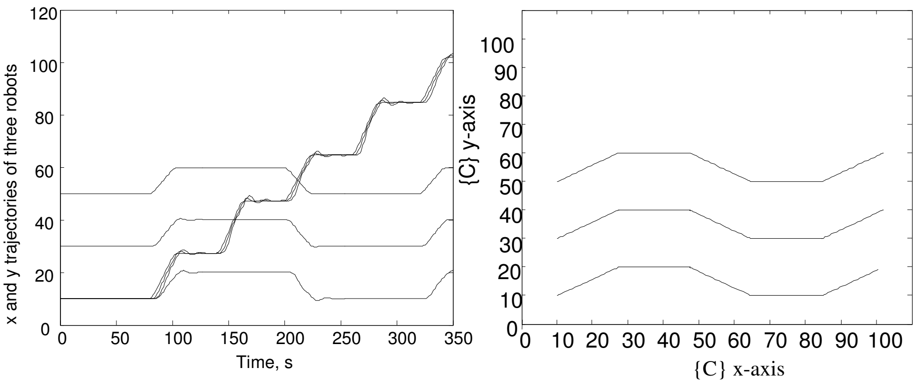


Figure 7. Unequal dynamics of following robots result in spatial errors. Corrected by controller.

Table 1 shows the final x-y positions of the three robots after completing the five rotations and translations with local controllers that produce steady state errors. The overall control scheme that uses sensor signals is able to reduce the errors and position the robots close to the required nominal distance of 20 y-units.

| | Desired x | Actual x | x-error | Desired y | Actual y | y-error |
|---|---|---|---|---|---|---|
| Robot 1 | 102 | 101.9549 | -0.0451 | 60 | 59.9842 | -0.0158 |
| Robot 2 | 102 | 102.3427 | 0.3427 | 40 | 40.2080 | 0.2080 |
| Robot 3 | 102 | 103.2089 | 1.2089 | 20 | 20.7058 | 0.7058 |

Figure 8 shows the trajectories for a horizontal chain of three robots obtained by using the control scheme . Rotation trajectories of the three robots and translation motion of the leader robot are shown in the figure (Top Left). Robot forward motion trajectories resulting from feedback control are shown in the Top right figure. The other two figures show the spatial motion of the three robots in the World frame {C}. The robots maintain the correct distance between each other as they execute a motion that requires rot(z, -60°), trans(y, r), then rot(z, -120°), trans(y, r), then rot(z, -60°), trans(y, r), then requires rot(z, -120°), trans(y, r), and final two more rot(z, -60°), trans(y, r).

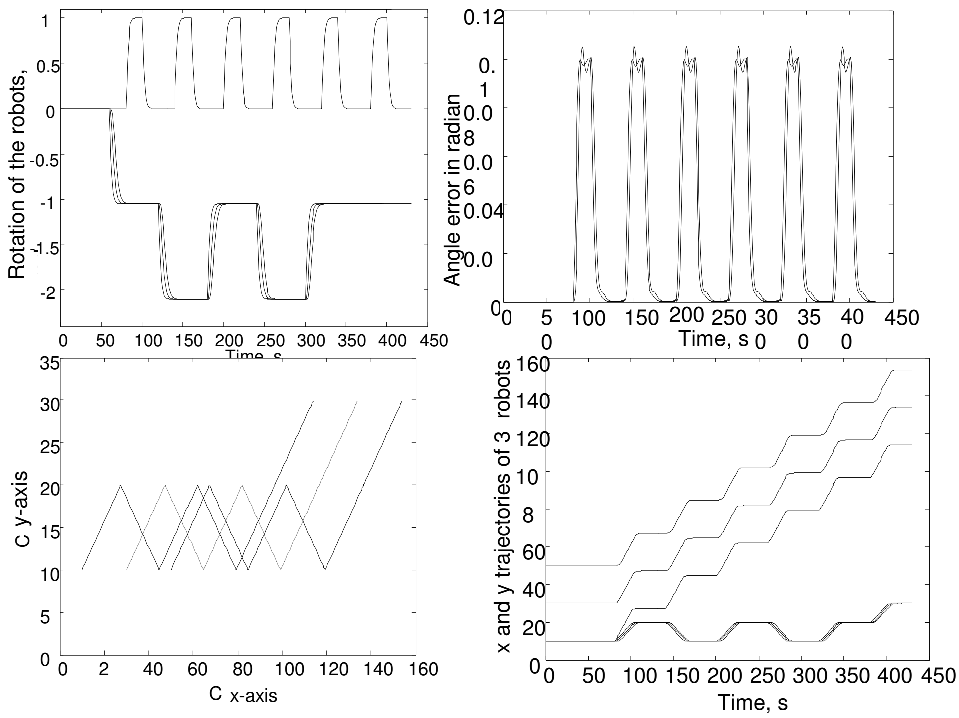


Figure 8. Horizontal chain of three robots. Motion trajectories produced by the control scheme.

When the horizontal chain is required to move in the plus or minus ninety degrees direction, the angular error will be zero. In this case the link error can be used to decide how to move the robots. Also for the vertical chain of robots, a zero degree rotation i.e. move straight up or down will also result in zero angular error and again the link length error will be required to follow the leader robot.

## 6. Conclusion

To achieve the objective of a fully reactive collective of robots that preserves its structure during motion a feedback control strategy is employed that uses physical links to sense the relative motion of neighbouring robots and attempts to maintain a desired direction angle and distance between the robots. The control scheme is able to deal with differences in dynamics between the robots and errors in the local controllers of each robot.

## 7. References


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