Decentralized Coordination of Networked Cobots: A Graph-Theoretic Approach to Object Transportation

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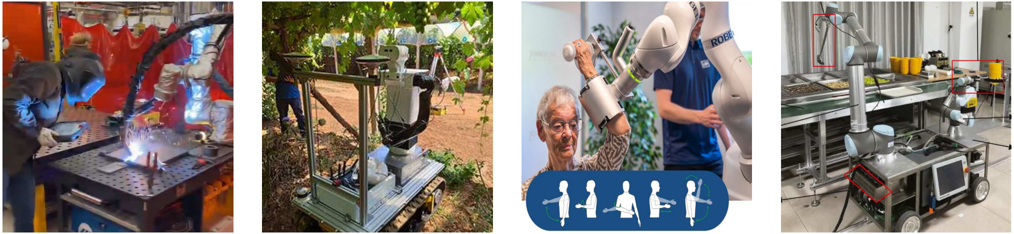
Collaborative robots (Cobots): robots designed to assist humans in completing tasks, or to work simultaneously with human in the same workspace [1]



(a) (b) (c) (d)

Figure 1: Application of cobots in (a) manufacturing [2], (b) agriculture [3], (c) healthcare [4], and (d) service industries [5].

Introduction

Objective

Cooperative object transportation using autonomous network cobots for industrial applications

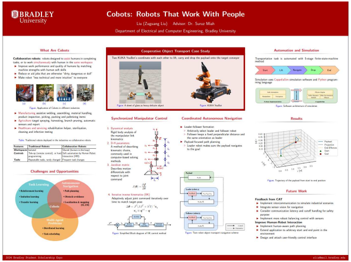
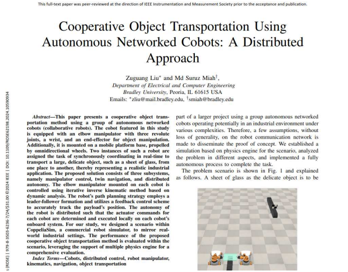


Figure 2: Poster presented at 2024 Student Scholarship Expo and Engineering Open House



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Cooperative Object Transportation Using Autonomous Networked Cobots: A Distributed Approach

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***Abstract*—This paper presents a cooperative object transportation method using a group of autonomous networked cobots (collaborative robots). The cobot featured in this study is equipped with an elbow manipulator with three revolute joints, a wrist, and an end-effector for object manipulation. Additionally, it is mounted on a mobile platform base, propelled by omnidirectional wheels. Two instances of such a robot are assigned the task of synchronously coordinating in real-time to transport a large, delicate object, such as a sheet of glass, from one place to another, thereby representing a realistic industrial application. The proposed solution consists of three subsystems, namely manipulator control, twin navigation, and distributed autonomy. The elbow manipulator mounted on each cobot is controlled using iterative inverse kinematic method based on dynamic analysis. The robot's path planning strategy employs a leader-follower formation and utilizes a feedback control scheme to accurately track the payload's position. The autonomy of the robot is distributed such that the actuator commands for each cobot are determined and executed locally on each cobot's onboard system. For our study, we designed a scenario within CoppeliaSim, a commercial robot simulator, to mirror real-world industrial settings. The performance of the proposed cooperative object transportation method is evaluated within the scenario, leveraging the support of multiple physics engine for a comprehensive evaluation.**

***Index Terms*—Cobots, distributed control, robot manipulator, kinematics, navigation, object transportation**

part of a larger project using a group autonomous networked cobots operating potentially in an industrial environment under various complexities. Therefore, a few assumptions, without loss of generality, on the robot communication network is made to disseminate the proof of concept. We established a simulation based on physics engine for the scenario, analyzed the problem in different aspects, and implemented a fully autonomous process to complete the task.

The problem scenario is shown in Fig. 1 and explained as follows. A sheet of glass as the delicate object is to be

Figure 3: Conference paper accepted at 2024 IEEE International Symposium on Robotic and Sensors Environments (ROSE) [6]

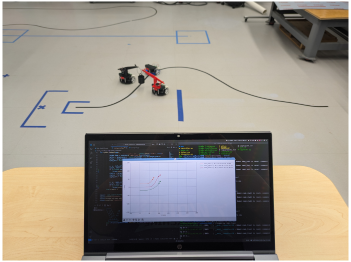

Figure 4: Proof-of-concept system for real-life experimentation (video demo)

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Figure 5: Transportation using push-pull strategy and leader-follower formation [7]

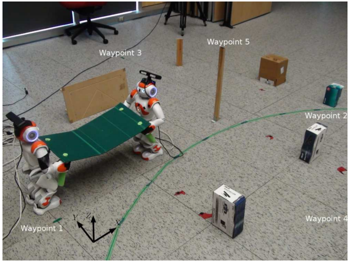

Figure 6: Transportation using two humanoid robots [8]

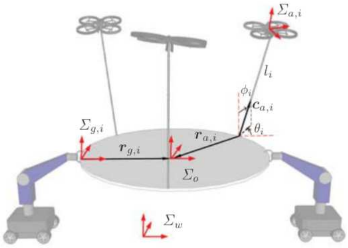

Figure 7: Transportation using heterogeneous robots [9]

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Graph Theoretic Approach

Fully Connected Graph Model

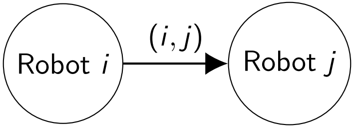

Figure 8: Graph of two robots i and j

Adjacency Matrix: representation of the edges

$$A_{ij} = \begin{cases} 1 & \text{if } (i,j) \in \mathcal{E} \\ 0 & \text{otherwise} \end{cases}$$

Out-Degree Matrix: the number of outgoing edges on the diagonal [10]

$$D_{ii} = \sum_{j=1}^{n} A_{ij}$$

Laplacian Matrix: characterizes the consensus dynamics of the network [11]

$$\mathbf{L} = \mathbf{D} - \mathbf{A}$$

One of the key characteristics of the Laplacian matrix is its eigenvalues

$$\mathbf{L}\boldsymbol{v} = \lambda\boldsymbol{v},$$

The eigenvalues have properties:

- All eigenvalues are non-negative
- For a fully connected graph, there is exactly one zero eigenvalue
- The second smallest eigenvalue describes its **algebraic connectivity**

Graph Theoretic Approach

Robot Network Topologies

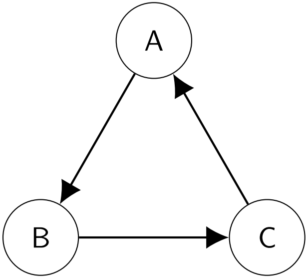

Figure 9: Cyclic topology

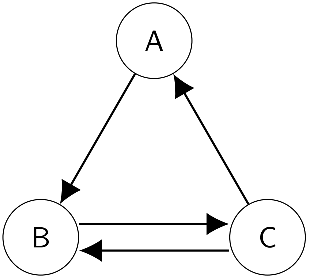

Figure 10: Cyclic topology with back link

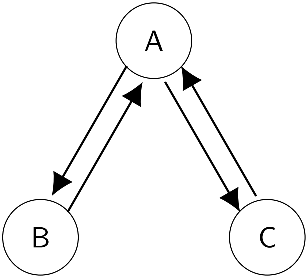

Figure 11: Star topology

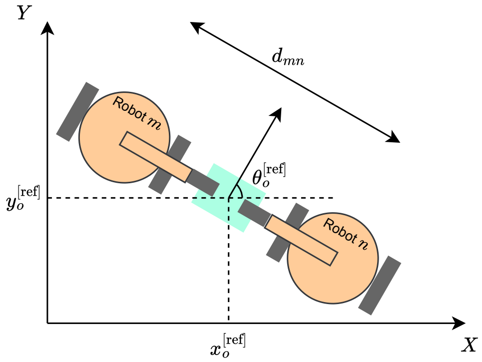

Figure 12: Robot m and Robot n with respect to payload

$$\boldsymbol{q}_m^{[\text{ref}]} = \begin{bmatrix} x_m \\ y_m \\ \theta_m \end{bmatrix} = \begin{bmatrix} x_o^{[\text{ref}]} - \frac{d_{mn}}{2}\sin\left(\theta_o^{[\text{ref}]}\right) \\ y_o^{[\text{ref}]} + \frac{d_{mn}}{2}\cos\left(\theta_o^{[\text{ref}]}\right) \\ \theta_o^{[\text{ref}]} \end{bmatrix}$$

$$\boldsymbol{q}_n^{[\text{ref}]} = \begin{bmatrix} x_n \\ y_n \\ \theta_n \end{bmatrix} = \begin{bmatrix} x_o^{[\text{ref}]} + \frac{d_{mn}}{2}\sin\left(\theta_o^{[\text{ref}]}\right) \\ y_o^{[\text{ref}]} - \frac{d_{mn}}{2}\cos\left(\theta_o^{[\text{ref}]}\right) \\ \theta_o^{[\text{ref}]} \end{bmatrix}$$

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Robot Kinematic Model

Differential Drive Mobile Robot

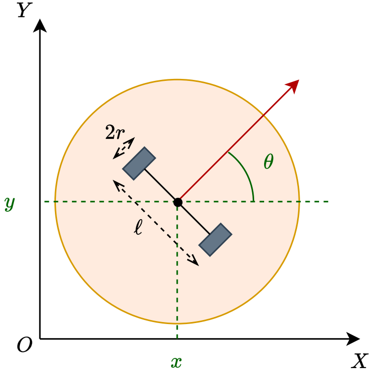
Forward kinematics:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \frac{r}{2} \begin{bmatrix} \cos(\theta) & \cos(\theta) \\ \sin(\theta) & \sin(\theta) \\ 2/\ell & -2/\ell \end{bmatrix} \begin{bmatrix} \omega_l \\ \omega_r \end{bmatrix}$$

Inverse kinematics simplifies into a unicycle model:

$$\begin{bmatrix} \omega_l \\ \omega_r \end{bmatrix} = \frac{1}{r} \begin{bmatrix} 1 & \ell/2 \\ 1 & -\ell/2 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}$$

where linear velocity $v = \sqrt{\dot{x}^2 + \dot{y}^2}$,
angular velocity $\omega = \dot{\theta}$



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Forward kinematics:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} l_1 \cos\phi_1 + l_2 \cos(\phi_1 + \phi_2) \\ l_1 \sin\phi_1 + l_2 \sin(\phi_1 + \phi_2) \end{bmatrix}$$

Inverse kinematics:

$$\phi_2 = \arccos\left(\frac{x^2 + y^2 - l_1^2 - l_2^2}{2 l_1 l_2}\right),$$

$$\phi_1 = \arctan\left(\frac{y}{x}\right) - \arctan\left(\frac{l_2 \sin\phi_2}{l_1 + l_2 \cos\phi_2}\right).$$

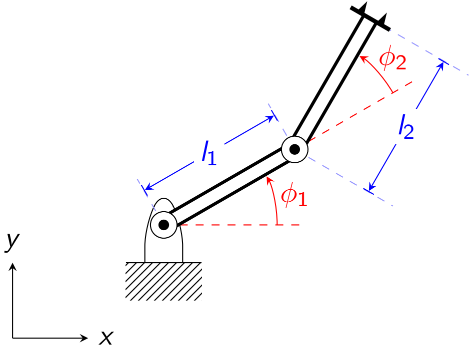

Figure 13: 2-DOF R-R manipulator

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Computer Simulation
Problem Setup

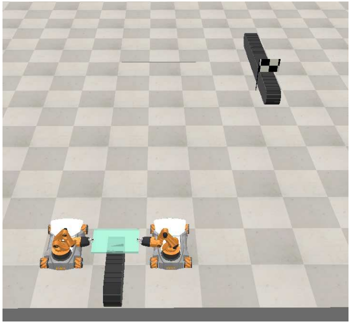

Figure 14: Problem scenario in CoppeliaSim (video demo)

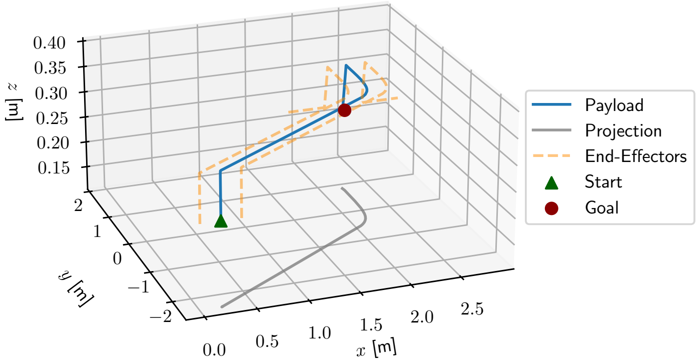

Figure 15: Trajectory of the payload

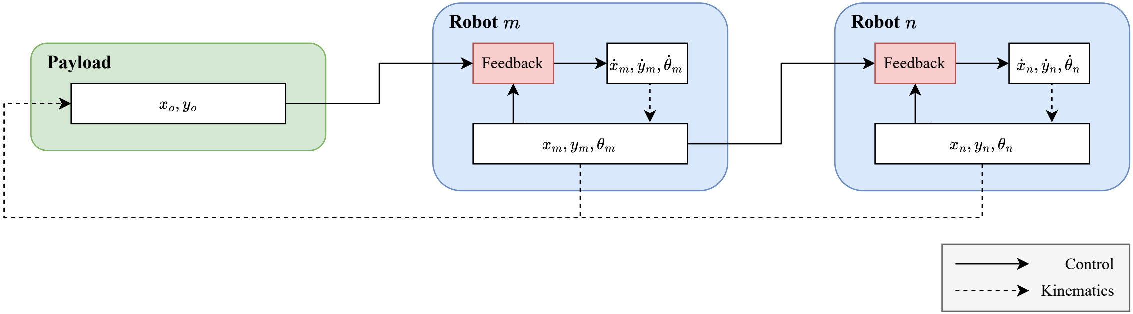

Figure 16: Twin robot object transport navigation scheme

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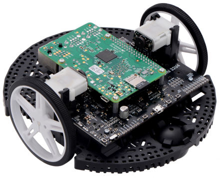

Figure 17: Pololu Romi mobile robot

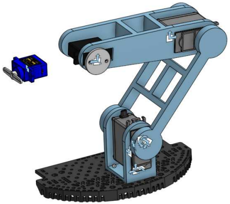

Figure 18: 3D printed arm attached to top plate

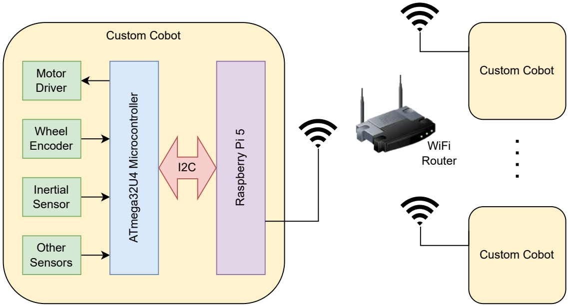

Figure 19: Top-level hardware architecture

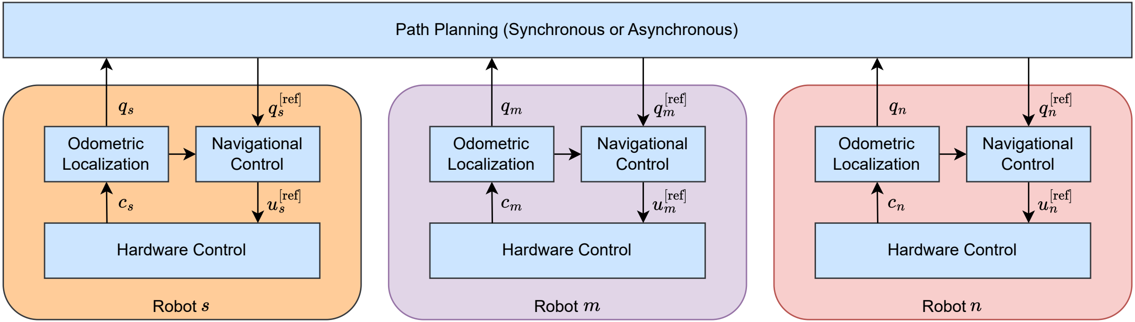

Figure 20: High-level control architecture for the Romi mobile robot

Implementation

Intermittent Communication Handling

Algorithm 1 Psuedocode when robot i loses connection

Require: $\boldsymbol{q}_s, \dot{\boldsymbol{q}}_s, \boldsymbol{q}_m, \dot{\boldsymbol{q}}_m, \boldsymbol{q}_n, \dot{\boldsymbol{q}}_n$ ▷ *states of all robots*

while true **do** attempt reconnect
    if success **then** ▷ *return to normal operation*
        break
    else
        $\boldsymbol{q}_i \leftarrow \textsc{OdometricLocalization}(\boldsymbol{q}_i, \boldsymbol{c}_i)$
        for robot j in all other robots **do**
            $\boldsymbol{q}_j \leftarrow \textsc{DeadReckoning}(\boldsymbol{q}_j, \dot{\boldsymbol{q}}_j)$
            if $\textsc{EuclideanDistance}(\boldsymbol{q}_i, \boldsymbol{q}_j) < \varepsilon$ **then** ▷ *safety distance*
                $\dot{\boldsymbol{q}}_i \leftarrow \boldsymbol{0}$
            else
                Keep $\dot{\boldsymbol{q}}_i$ unchanged

Implementation

Experiment Results

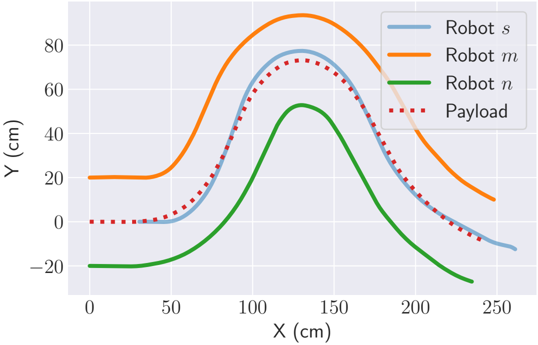

Figure 21: Trajectory of robots using synchronous path planning (demo video)

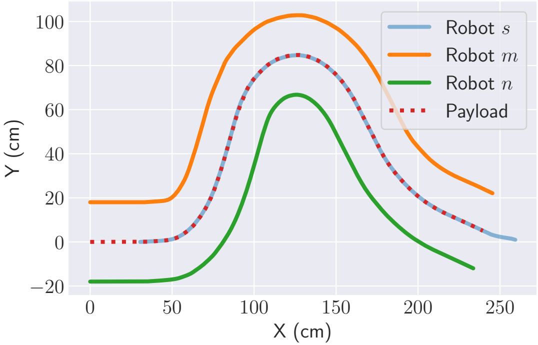

Figure 22: Trajectory of robots using asynchronous path planning (demo video)

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Conclusion

Thesis contribution

- Case study on cooperative object transportation using autonomous network cobots
- Graph-theoretic approach to decentralized coordination
- "Sim-to-Real" validation using computer simulation and real-life experimentation

Conclusion

Thesis contribution

- Case study on cooperative object transportation using autonomous network cobots
- Graph-theoretic approach to decentralized coordination
- "Sim-to-Real" validation using computer simulation and real-life experimentation

Future work

- Complete implementation of the manipulator arm
- Adopt better-performant wireless mesh technology for communication
- Extend the system to include more robots and complex tasks

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Thank you! Any questions?

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