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Distributed Optimization Framework for Industry 4.0 Automated Warehouses

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Abstract

Robotic automation is being increasingly proselytized in the industrial and manufacturing sectors to increase production efficiency. Typically, complex industrial tasks cannot be satisfied by individual robots, rather coordination and information sharing is required. Centralized robotic control and coordination is ill-advised in such settings, due to high failure probabilities, inefficient overheads and lack of scalability. In this paper, we model the interactions among robotic units using *intelligent agent* based interactions. As such agents behave autonomously, coordinating task/resource allocation is performed via distributed algorithms. We use the motivating example of warehouse inventory automation to optimally allocate and distribute delivery tasks among multiple robotic agents. The optimization is decomposed using *primal* and *dual* decomposition techniques to operate in minimal latency, minimal battery usage or maximal utilization scenarios. These techniques may be applied to a variety of deployments involving coordination and task allocation between autonomous agents.

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1. Introduction

Integration of robotics, cyber-physical systems and the cloud has come to the forefront with Industry 4.0 [1] requirements. Industry 4.0 proposes the "smart factory" solution, wherein, modular cyber-physical systems coordinate to make decentralized decisions. Such coordination is required for high throughput, complex flows among multiple participants in industrial deployments. Some of the key requirements include [1]:

1. *Interoperability*: Machines, Internet of Things (IoT) [2] enabled devices and humans connected and coordinating with each other.

2. *Information transparency*: Physical systems enhanced with sensor data to create added value information systems.

3. *Technical Assistance*: This involves the use of intelligent devices to aid in informed decision making. Robotic automation may be identified to perform repetitive, unsafe or precise tasks.

4. *Decentralized Decisions*: The ability of such systems to make autonomous decisions; only critical cases will involve human intervention.

Warehouse and factory floor automation [3][4] has been a principal area of interest with respect to these requirements. Automated Guided Vehicles (AGVs) are employed in the warehousing environment to move products from one place to another [5][6]. AGVs follow fixed routes (using wires or markers) that are pre-programmed on them. As they have limited on board computational intelligence, *Networked Robotics* [7] have been proposed, where robotic AGVs may link to an internet based infrastructure to seamlessly exchange data. This data may be autonomously exchanged or co-ordinated via a central control station. This has been extended to the *Cloud Robotics* [8] framework, where robots make use of the cloud to coordinate or offload computational tasks.

In warehouses that may have hundreds of robots on the shop floor, complex problem domains (scheduling, optimization, planning) require modular and scalable solutions [4]. A number of functional, modular components (agents) may be deployed to solve specialized problem aspects. Decomposing large problems allows

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the Industry 4.0 automation requirements in warehouses. Through the use of decomposed optimization techniques, the intelligent agents are efficiently enabled utilization, latency and energy resources when traded off with task allocation. Through distributed optimization solvers, these situations are analyzed based on commercially available warehouse robots to demonstrate efficacy in delivery tasks. Such a distributed optimization framework may be extended to other deployments involving intelligent agents.

In future, we would like to deploy this framework on testbed deployments defined using the Robot Operating System (ROS). Incorporating our optimization framework within an auction bid mechanism along with human agents is also another aspect for future consideration.

References

[1] M. Hermann, T. Pentek & B. Otto, "Design Principles for Industrie 4.0 Scenarios", *49th Hawaii Intl. Conf. on System Sciences*, 2016.

[2] S. Greengard, "The Internet of Things", *MIT*, 2015.

[3] M. Hompel & T. Schmidt, "Warehouse Management: Automation and Organization of Warehouse and Order Picking Systems", *Springer-Verlag*, 2012.

[4] J. Bartholdi & S. Hackman, "Warehouse and Distribution Science", *The Supply Chain and Logistics Institute*, Georgia Institute of Technology, 2016.

[5] V. Marik & D. McFarlane, "Industrial Adoption of Agent-Based Technologies", *IEEE Intelligent Manufacturing Control*, 2005.

[6] W. Shen, "Distributed Manufacturing Scheduling using Intelligent Agents", *IEEE Intelligent Systems*, 2002.

[7] R. Luo, K. Su, S. Shen & K. Tsai, "Networked intelligent robots through the Internet: issues and opportunities", *IEEE Magazine*, vol. 91, no. 3, pp. 371–382, 2003.

[8] G. Hu, W. Tay & Y. Wen, "Cloud robotics: architecture, challenges and applications", *IEEE Network*, vol. 26, no. 3, pp. 21–28, 2012.

[9] K. Sycara, "Multiagent Systems", *AI Magazine: Intelligent Agents*, vol. 19, No.2, 1998.

[10] Y. Shoham & K. Leyton-Brown, "Multiagent Systems: Algorithmic, Game-Theoretic, and Logical Foundations", *Cambridge University Press*, 2009.

[11] JDA Warehouse Management System (WMS), https://jda.com/solutions/profitable-omni-channel-retail-solutions/intelligent-fulfillment/warehouse-management, 2017.

[12] T. Sandholm, "An Implementation of the Contract Net Protocol Based on Marginal Cost Calculations," *University of Massachusetts*, 1993.

[13] Flavio Bonomi, Rodolfo Milito, Preethi Natarajan & Jiang Zhu, "Fog Computing: A Platform for Internet of Things and Analytics", *Big Data and Internet of Things: A Roadmap for Smart Environments*, pp. 169–186, 2014.

[14] P. Wurman, R. D'Andrea & M. Mountz, "Coordinating Hundreds of Cooperative, Autonomous Vehicles in Warehouses", *AAAI Artificial Intelligence Mag.*, vol. 29, no. 1, pp. 9–19, 2008.

[15] B. Hardgrave, J. Aloysius & S. Goyal, "Does RFID improve inventory accuracy? A preliminary analysis", *Intl. J. of RF Technologies*, vol. 1, no. 1, pp. 44–56, 2009.

[16] S. Boyd & L. Vandenberghe, "Convex Optimization", *Cambridge University Press*, 2004.

[17] A. Nedic & A. Ozdaglar, "Cooperative distributed multi-agent optimization", *Convex Optimization in Signal Processing and Communications*, Cambridge University Press, 2009.

[18] H. Terelius, U. Topcu & R. Murray, "Decentralized Multi-Agent Optimization via Dual Decomposition", *IFAC Proceedings Volumes*, vol. 44, no. 1, pp. 11245–11251, 2011.

[19] D. Palomar & M. Chiang, "A Tutorial on Decomposition Methods for Network Utility Maximization", *IEEE J. on Selected Areas in Communications*, vol. 24. no. 8, 2006.

[20] A. Kattepur, H. Dohare, V. Mushunuri, H. Rath & A. Simha, "Resource Constrained Offloading in Fog Computing", *ACM Middleware Workshops*, 2016.

[21] R. Rao, S. Vrudhula & D. Rakhmatov,"Battery Modeling for Energy-Aware System Design", *IEEE Computer*, vol. 36, no. 12, 2003.

[22] A. Hausmann & C. Depcik, "Expanding the Peukert equation for battery capacity modeling through inclusion of a temperature dependency", *J. of Power Sources*, vol. 235, pp 148–158, 2013.

[23] W. Shen, Q. Hao, H. Yoon & D. Norrie, "Applications of agent-based systems in intelligent manufacturing: An updated review", *Advanced Engineering Informatics* vol. 20, pp. 415–431, 2006.

[24] B. Brummit, "A Mission Planning System for Multiple Mobile Robotics in Unknown, Unstructured, and Changing Environments", *tech. report CMU-RI-TR-98-42*, Robotics Institute, Carnegie Mellon University, 1998.

[25] L. Panait & S. Luke, "Cooperative Multi-Agent Learning: The State of the Art", *Autonomous Agents and Multi-Agent Systems*, 11, pp. 387–434, 2005.

[26] M. Fletcher, R. Brennan & D. Norrie, "Modeling and reconfiguring intelligent holonic manufacturing systems with internet-based mobile agents," *Journal of Intelligent Manufacturing*, no. 14, vol. 1, pp. 7–23, 2003.

[27] A. Cardon, T. Galinho & J. Vacher, "Genetic algorithms using multi-objectives in a multi-agent system," *Robotics and Autonomous Systems*, no. 33, pp. 179–190, 2000.

[28] Frantisek Duchon, Andrej Babinec, Martin Kajan, Peter Beno, Martin Florek, Tomas Fico & Ladislav Jurisica, "Path Planning with Modified a Star Algorithm for a Mobile Robot", *Procedia Engineering*, vol. 96, pp. 59–69, 2014.