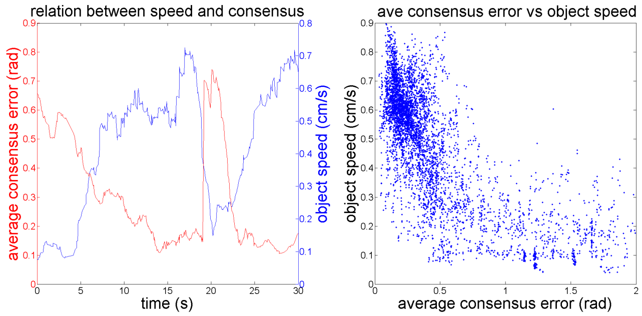

Figure 9: (Left) The average consensus error and object speed during a test of consensus-based transport during startup and during a manual disturbance (at time=18 s) to robot headings. (Right) A scatterplot of object speed vs. average consensus error for 1/10th of a second intervals during 5 tests of consensus-based transport.

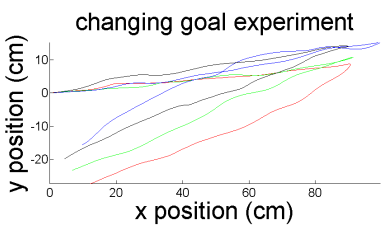

Figure 10: The path of an object during four experiments where the goals changes mid-experiment. Object starts on left, moves towards first goal to the right, then goal moves to lower left.

strations that are unique to this method. For example, the simplicity and scalability of this method allowed for a demonstration of 100 Kilobots transporting an object (fig. 1). Since this method for transport is agnostic to object shape, it can even transport an object whose shape is slowly changing or an actively moving shape. In nature, ants have been observed carrying wiggling worms, but this has never been shown in artificial systems. To demonstrate this, an experiment was designed where Kilobots transported a shape that had an actively articulated joint, which caused the object to "squirm" while it was transported, see fig. 1. Additionally, as the algorithm is memoryless, it can allow changing or moving goal location. Fig. 10 shows the path of transport during an experiment where the goal location is changed mid-experiment.

5. CONCLUSION

In this paper, we investigate a simple decentralized method for collective transport and present both theory and experiments to evaluate this method. Using a physics-based model, we are able to show that, given enough agents to overcome static friction, the method is guaranteed to move the object in an optimal straight-line path to the goal with no more than 180° of rotation. Additionally, this method does not require agents to know object shape, center-of-mass, precise attachment points, or number of other agents. This method allows for agents with limited capabilities to complete complex transport tasks, provided an agent can determine goal direction. We also show how simple inter-agent communication of heading, similar to flocking, can allow agents to collectively transport objects even when some or most lack knowledge of goal location.

For future work, this physical model may be useful for analyzing other collective transport strategies, for example strategies where robots can only apply forces in a limited direction (e.g., only push) and therefore may need to detach and reattach in different locations to move the object [1]. Another area of future research is to compare our model to transport by ants, such as *Pheidologeton diversus* [2], where ants appear to apply force in the nest direction by surrounding the object such that ants in front are walking backwards and pulling, ants in the back push, and ants on the sides shuffle sideways [2]. By designing specific objects and scenarios [3], it may be possible to compare the behavior of ant transport with the results from our models and experiments.

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7. REFERENCES

[1] E. Bonabeau *et al*, Swarm intelligence: From Natural to Artificial Systems, Chapter 7, 1999.

[2] M. Moffett, Cooperative Food Transport By an Asiatic Ant, National Geographic Research, vol. 4 (386-394), 1988.

[3] S. Berman *et al*, Study of Group Food Retrieval by Ants as a Model for Multi-Robot Collective Transport Strategies, RSS 2010.

[4] D. Stilwell, J. Bay, Toward the development of a material transport system using swarms of ant-like robots, ICRA 1993.

[5] R. Gross, M. Dorigo, Towards Group Transport by Swarms of Robots, International Journal of Bio-Inspired Computation, 1(1-2):1-13, 2009.

[6] R. Gross *et al*, Object Transport by Modular Robots that Self-Assemble, ICRA 2006.

[7] A. Campo *et al*, Negotiation of goal direction for cooperative transport, ANTS 2006.

[8] G. Montemayor, J. Wen, Decentralized Collaborative Load Transport by Multiple Robots, ICRA 2005.

[9] Q. Lindsey, M. Shomin, V. Kumar, Cooperative Quasi-Static Planar Manipulation with Multiple Robots, IDETC/CIE 2010.

[10] H. Su, V. Krovi, Decentralized Dynamic Control of a Nonholonomic Mobile Manipulator Collective: a Simulation Study, ASME-DSCC 2008.

[11] M. Rubenstein *et al*, Kilobot: A Low Cost Scalable Robot System for Collective Behaviors, ICRA 2012.

[12] J. McLurkin *et al*, A Low-Cost Multi-Robot System for Research Teaching and Outreach, DARS 2010.

[13] P. Muir, C. Neuman, Kinematic Modeling for Feedback Control of an Omnidirectional Wheeled Mobile Robot, ICRA 1987.

[14] E. Olson, AprilTag: A Robust and Flexible Visual Fiducial System, ICRA 2011.

[15] I. Couzin, J. Krause, N. Franks, S. Levin, Effective Leadership and Decision Making in Animal Groups on the Move, Nature, 433 (513-516) 2005.

[16] H. Tanner, A. Jadbabaie, G. Pappas, Stable flocking of mobile agents, Part I: Fixed topology, CDC 2003.