Independent Navigation of Multiple Robots and Virtual Agents

Jamie Snape
University of North Carolina at Chapel Hill
snape@cs.unc.edu

Stephen J. Guy
University of North Carolina at Chapel Hill
sjguy@cs.unc.edu

Jur van den Berg
University of California, Berkeley
berg@berkeley.edu

ABSTRACT

We demonstrate an approach for collision- and oscillation-free navigation of multiple robots or virtual agents amongst each other. Each entity acts independently and uses only both the position and velocity of nearby entities to predict their future trajectories in order to avoid collisions. Entities take into account that the other entities are responding to them likewise to prevent oscillations.

Categories and Subject Descriptors

I.2.9 [**Artificial Intelligence**]: Robotics; I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence

General Terms

Algorithms, experimentation

Keywords

Planning, multi-robot systems

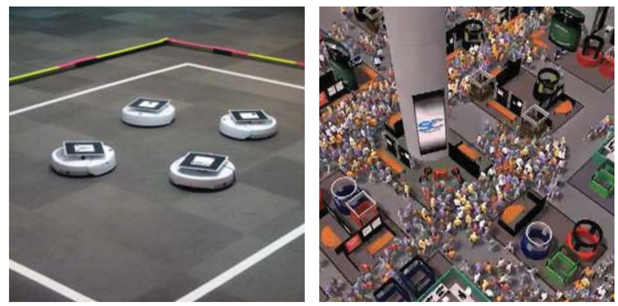
1. INTRODUCTION

The problem of collision- and oscillation-free navigation of multiple robots or virtual agents arises in robotics, computer animation, virtual environments, crowd simulations, and traffic engineering.

Many works have examined the problem of collision-free navigation of a robot or virtual agent in an environment with dynamic obstacles [3, 4, 5, 6]. Most approaches predict where dynamic obstacles might be in the future by extrapolating their current velocities, and let the entity avoid collisions accordingly. However, this approach does not suffice when other robots or agents are encountered. Treating the other entities as dynamic obstacles overlooks their reciprocity, that is, these entities will react to another entity in the same way that the entity reacts to them. Hence, estimating the future trajectories of other entities by extrapolating their current velocities may cause undesirable oscillations in their motion [8].

We demonstrate the concept of optimal reciprocal collision avoidance [7] for navigation of multiple robots or virtual agents that explicitly considers this reciprocity. Reciprocity lets an entity take half of the responsibility of avoiding collisions with another entity and assumes that the other entity takes the other half. Each entity executes an independent continuous cycle of sensing and acting, in which an entity chooses its new velocity based on observations of the positions and velocities of the other entities.

Cite as: Independent Navigation of Multiple Robots and Virtual Agents, Jamie Snape, Stephen J. Guy, Jur van den Berg, Sean Curtis, Sachin Patil, Ming C. Lin, and Dinesh Manocha, *Proc. of 9th Int. Conf. on Autonomous Agents and Multiagent Systems (AAMAS 2010)*, van der Hoek, Kaminka, Lespérance, Luck and Sen (eds.), May, 10–14, 2010, Toronto, Canada, pp. 1645-1646



(a) (b)

Figure 1: (a) Four *iRobot Create* mobile robots. (b) Agents moving around a virtual trade show.

We have applied our approach to multiple mobile robots moving in an indoor environment, Fig. 1(a), and to a large crowd of several hundred virtual agents, Fig. 1(b). Our experiments show that our approach achieves natural, direct, and collision-free navigation in both applications.

2. PRIOR WORK

Prior work has often focused on the issue of a single entity navigating amongst multiple dynamic obstacles [4, 5, 6]. A successful concept is the velocity obstacle [3], which has inspired several variations more suited to systems of multiple robots or virtual agents, for example [8]. Generally these attempt to incorporate the reactive behavior of the other entities in the environment, though each have their own shortcomings.

Other work has focused on follow-the-leader behavior [2], while there is a large body of work on centrally coordinating the motions of multiple entities. Potential fields are used for multi-robot navigation in [1].

3. OPTIMAL RECIPROCAL COLLISION AVOIDANCE

Optimal reciprocal collision avoidance [7] is a velocity-based collision avoidance approach based on the idea of a

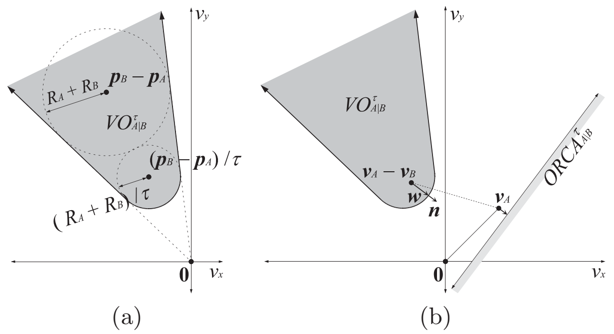


Figure 2: (a) The velocity obstacle $VO^{\tau}_{A|B}$. (b) The permitted velocities $ORCA^{\tau}_{A|B}$.

velocity obstacle [3].

Consider two disc-shaped entities A and B with radii r_A and r_B, positions $\boldsymbol{p}_A$ and $\boldsymbol{p}_B$, and velocities $\boldsymbol{v}_A$ and $\boldsymbol{v}_B$, respectively. The velocity obstacle $VO^{\tau}_{A|B}$ for A induced by B in the local time interval $[0, \tau]$, Fig. 2(a), is the set of velocities of A relative to B that will cause a collision between A and B at some moment before time τ has elapsed, assuming that both entities maintain a constant trajectory within that time interval:

$$VO^{\tau}_{A|B} = \{\boldsymbol{v} \mid \exists t \in [0, \tau] :: t(\boldsymbol{v} - \boldsymbol{v}_B) \in \mathrm{D}(\boldsymbol{p}_B - \boldsymbol{p}_A, r_A + r_B)\}.$$

If A and B each choose a velocity outside $VO^{\tau}_{A|B}$ and $VO^{\tau}_{B|A}$, respectively, then they will be collision-free for at least τ time.

The half-plane of velocities $ORCA^{\tau}_{A|B}$ available to A for optimal reciprocal collision avoidance with B in the local time interval $[0, \tau]$, Fig. 2(b), is defined as follows. Let $\boldsymbol{w}$ be from $\boldsymbol{v}_A - \boldsymbol{v}_B$ to the closest point on the boundary $\partial VO^{\tau}_{A|B}$. Moreover, let $\boldsymbol{n}$ be the outward normal of $\partial VO^{\tau}_{A|B}$ at $\boldsymbol{v}_A - \boldsymbol{v}_B + \boldsymbol{w}$, and assume that both A and B adapt their velocity by $\frac{1}{2}\boldsymbol{w}$ to avoid colliding with each other. Then the set of permitted velocities $ORCA^{\tau}_{A|B}$ is

$$ORCA^{\tau}_{A|B} = \{\boldsymbol{v} \mid (\boldsymbol{v} - (\boldsymbol{v}_A + \tfrac{1}{2}\boldsymbol{w})) \cdot \boldsymbol{n} \geq 0\}.$$

To make progress towards its goal, an entity A sharing an environment with a set of entities B_i should chose the velocity closest to one directed towards its goal that lies within the intersection of all half-planes $ORCA^{\tau}_{A|B_i}$. This may be found using linear programming.

4. DISCUSSION

Our demonstration, available at http://gamma.cs.unc.edu/INDNAV/, shows that our approach is applicable to navigating both multiple robots and crowds of virtual agents.

We use four *iRobot Create* robots, Fig. 1(a), tracked by an overhead camera and controlled over Bluetooth from a central computer. The robots navigate through three scenarios without communicating with each other. In the first and second, two and four robots, respectively, must navigate from one corner of a rectangular environment to the opposite corner on the diagonal. They meet and have to navigate around each other in the middle. In the third scenario, one robot is a dynamic obstacle traveling across the environment at a constant velocity. The other robots cross its path to navigate to their goals. The motion generated by our approach is direct and collision-free with no noticeable oscillations, therefore showing an improvement on earlier velocity obstacle formulations [3, 8].

In the context of crowd simulations, we navigate hundreds of virtual agents through a large exhibition space containing a trade show, Fig. 1(b). The agents avoid both each other and static obstacles, such as the trade show exhibits, to reach one of the six labeled exits. The agents use a roadmap for global navigation. In contrast to approaches based on potential fields, such as [1], virtual agents in our simulation may pass closely by static obstacles with oscillation.

5. CONCLUSION

We have demonstrated the concept of optimal reciprocal collision avoidance for collision- and oscillation free navigation of multiple robots or virtual agents sharing an environment. We have shown that our approach is applicable to both the navigation of multiple mobile robots and the simulation of a large crowd of virtual agents.

6. ACKNOWLEDGMENTS

This work was supported in part by ARO contract W911NF-04-1-0088; NSF awards 0636208, 0917040, and 0904990; DARPA/RDECOM contract WR91CRB-08-C-0137; and Intel.

7. ADDITIONAL AUTHORS

Sean Curtis, Sachin Patil, Ming C. Lin, and Dinesh Manocha (University of North Carolina at Chapel Hill, {seanc,sachin, lin,dm}@cs.unc.edu).

8. REFERENCES

[1] J. Baxter, E. Burke, J. Garibaldi, and M. Norman. Multi-robot search and rescue: A potential field based approach. In *Autonomous Robots and Agents*, volume 76 of *Stud. Comput. Intell.*, pages 9–16. Springer, 2007.

[2] S. Carpin and L. E. Parker. Cooperative motion coordination amidst dynamic obstacles. In *Proc. Int. Symp. Distrib. Auton. Robot. Syst.*, pages 145–154, 2002.

[3] P. Fiorini and Z. Shiller. Motion planning in dynamic environments using velocity obstacles. *Int. J. Robot. Res.*, 17(7):760–772, 1998.

[4] D. Fox, W. Burgard, and S. Thrun. The dynamic window approach to collision avoidance. *IEEE Robot. Autom. Mag.*, 4:23–33, 1997.

[5] D. Hsu, R. Kindel, J.-C. Latombe, and S. Rock. Randomized kinodynamic motion planning with moving obstacles. *Int. J. Robot. Res.*, 21(3):233–255, 2002.

[6] S. Petti and T. Fraichard. Safe motion planning in dynamic environments. In *Proc. IEEE RSJ Int. Conf. Intell. Robot. Syst.*, pages 2210–2215, 2005.

[7] J. van den Berg, S. J. Guy, M. Lin, and D. Manocha. Reciprocal n-body collision avoidance. In *Proc. Int. Symp. Robot. Res.*, 2009.

[8] J. van den Berg, M. Lin, and D. Manocha. Reciprocal velocity obstacles for real-time multi-agent navigation. In *Proc. IEEE Int. Conf. Robot. Autom.*, pages 1928–1935, 2008.