Self-organizing robot formations using velocity potential fields commands for material transfer

Dan Sorin Necsulescu, Elisha Pruner & Jurek Sasiadek

Published online: 15 Sep 2014.

Submit your article to this journal ⬚

Article views: 382

View related articles ⬚

View Crossmark data ⬚

Taylor & Francis
Taylor & Francis Group

Self-organizing robot formations using velocity potential fields commands for material transfer

Dan Sorin Necsulescu[a]*, Elisha Pruner[a] and Jurek Sasiadek[b]

[a]*Department of Mechanical Engineering, University of Ottawa, 770 King Edward Ave, Ottawa, Ontario, Canada K1N6N5;* [b]*Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, Canada*

Mobile robot formations differ in accordance with the mission, environment, and robot abilities. In the case of decentralized control, the ability to achieve the shapes of these formations needs to be built in the controllers of each autonomous robot. In this paper, self-organizing formations control for material transfer is investigated, as an alternative to automatic guided vehicles. Leader–follower approach is applied for controllers design to drive the robots toward the goal. The results confirm the ability of velocity potential approach for motion control of both self-organizing formations.

Keywords: mobile robots; velocity potential; self-organizing formations; decentralized control; leader–follower approach

1. Introduction

This paper presents a generic approach for autonomous mobile robots formations control in the case of an unknown environment, while avoiding stopping in a point of local equilibrium away from the goal. The approach, based on velocity potential method, does not have the drawback of the previous method, artificial potential field, that consists in possible local minima. This makes this approach of interest for material transfer applications. This paper presents the first velocity potential field approach for the control of formations of autonomous mobile robots and then investigates the ability of such formations of robots in transferring materials to workstations in the case that unexpected environment changes have to be accounted for.

Autonomous mobile robots can achieve formation motion under centralized control, for example, by teleoperation from a control center, or by decentralized control, achieving inter-robot motion coordination by individual robot controllers, Bahceci, Soysal, and Sahin (2003). The formations in this paper are assumed under decentralized control using a leader–follower approach. In this case, a follower vehicle is controlled with regard to the leader, such that the inter-robot relative distance is maintained in order to avoid collisions, while the robots are held together in the formation. In the case of decentralized control of autonomous robots, the followers do not have any prior knowledge of the goal of the leader, have no influence on its movements, and can only rely on its own sensors to adjust its linear and angular velocity to follow the leader. The

---

*Corresponding author. Email: necsu@uottawa.ca

paper uses a kinematic model for robot systems and presents a controller that is able to adjust the movement in a crowded environment, Li and Xiao (2005).

Planning and control of formations differ from the single robot case due to the varying sideway dimension of the formation and the possibility of changing its geometric shape. Two types of approaches were defined, self-organizing formations and predefined geometric formations, Fierro, Song, Das, and Kumar (2002), Siegwart et al. (2011), and Moshtagh, Nathan, Jadbabaie, and Danilidis (2009). First approach results in a continuous change of the formation geometry in real time and is computationally intensive. Second approach uses offline results for defining, simultaneously, formation shape and path planning, such that subsequent tracking control is less computationally intensive. In this paper, previous results regarding single robots are investigated and adapted to formations, Necsulescu, Pruner, Sasiadek, and Kim (2010). An alternative approach is based on behavioral control, Antonelliet, Arrichello, and Chiaverini (2009). Stabilization to a fixed goal was investigated using a polar coordinates controller to asymptotically stabilize a vehicle at the origin, Eghtesad and Necsulescu (2006). This methodology, along with, Jaydev et al. (1998), Fierro et al. (2002), Fierro and Song (2005), Roberti et al. (2009), and Necsulescu et al. (2010), helped to define an input–output linearization controller in polar coordinates to determine the bearing and range values of the follower.

In a pioneering paper, Arkin and Murphy (1990) study the use of autonomous mobile robots in flexible manufacturing systems as an alternative to autonomous guided vehicles that suffer from lack of flexibility. The authors propose the use of artificial intelligence for representing the knowledge required for achieving goal-oriented behaviors.

In an early paper, the integration of autonomous mobile robots in flexible manufacturing systems is investigated by Kupec (1989).

Arkin and Murphy (1990) published a comparison of the use of automatic guided vehicles (AGVs) and present preliminary results regarding autonomous robots in manufacturing. Simulation and experimental results target applications for flexible manufacturing systems.

Uny Cao (1997) published an early overview of the cooperative mobile robots, outlining existing results, and theoretical problems not yet solved.

Nathan and Kumar (1998) presented an approach for controlling shapes of ensembles of robots of finite size with nonholonomic constraints.

Hu and Brady (1997) propose a probabilistic approach for global path planning in the presence of uncertainty for mobile robots in a manufacturing environment using a topological graph. An optimal robot path is searched using dynamic programming.

Hu and Gu (1999) investigate the landmark-based navigation of autonomous robots used in manufacturing and present a new navigation algorithm that locates the robots and updates landmarks in a dynamic manufacturing environment.

A new approach to the design of the architecture of a computer-integrated manufacturing system is presented by Fisher (1999), based on hierarchical and decentralized concepts. Kalman filter algorithms are used for the fusion of odometry data with scanner data. Landmarks in the manufacturing environment are recognized using Kohonen neural networks.

Yamashita et al. (2000) propose a motion planning method for cooperative transportation of a large object by multiple mobile robots in a 3D environment. In order to avoid exploding computational time for larger systems, the authors divide a motion planner into a local manipulation planner and a global path planner.

Yamada et al. (2003) propose a 3D simulation environment for layout optimization of manufacturing cells and optimization of allocation of mobile robots in reconfigurable manufacturing systems using particle swarm optimization.

Motion planning of multiple mobile robots for cooperative manipulation and transportation is investigated by Yamashita et al. (2003). The dimensions of the configuration space (C-space) of the global path planner were reduced using features of the transportation by mobile robots. The potential field was used to find the solution by searching in this smaller dimension reconstructed C-space.

The Daigle et al. (2007) paper focuses on fault diagnosis in formations of mobile robots used in manufacturing. The study concludes that a centralized approach is computationally complex and requires intensive inter-robot communications, while a distributed approach, based on bond graph modelling, presents advantages in the presence of uncertainties.

Bischoff et al. (2010) present an industrial perspective regarding a new lightweight robot for industrial and service robotics applications with high performance, intended to serve future manufacturing.

In this paper, the use of self-organizing formations control for material transfer is investigated, as an alternative to AGVs. The control approach is based on velocity potential approach, proposed by Necsulescu, Pruner, Kim, and Sasiadek (2012) for motion control of both self-organizing formations and tested here for material transfer to assembly stations.

2.   Autonomous robot control using velocity potential approach

2.1.   *Velocity potential field approach*

Extensive work has been carried out for mobile robots path planning. Most of the results were developed for point mass holonomic vehicles. Artificial potential field and Virtual force field approaches were used for planning a path that avoids collisions with known obstacles, Mastellone et al. (2008) and Siegwart et al. (2011). In the case of a formation, path planning has to include the effects of constraints on its possible sideway collisions. In this paper, computed velocity commands, obtained from velocity potentials defined in hydrodynamics, are used, instead of artificial potential fields approach, Kim
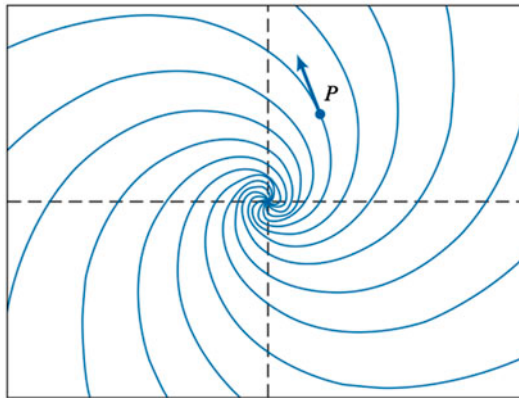

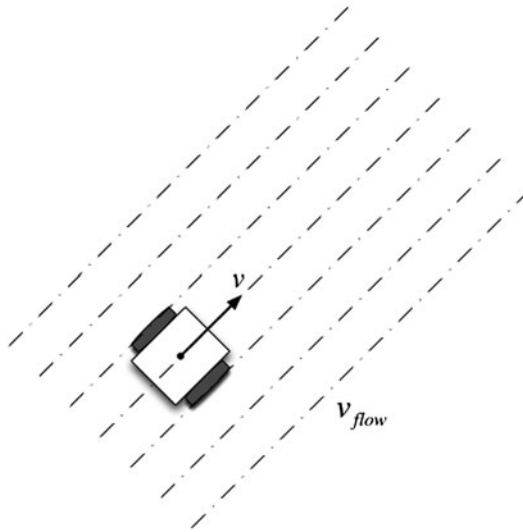Figure 1.   The flow in the case of combined source and vortex, Pruner (2013).

Figure 2. Differential-drive mobile robot moving with the attractive flow towards a goal position, Pruner (2013).

and Khosla (1992), Daily and Bevly (2008) Fahimi et al. (2008). In the case of velocity potentials, the gradient is a velocity, which is compatible to velocity commands to a kinematic model of the robots.

The gradient of harmonic velocity potentials for 2D is a logarithmic solution that has no local minimum if the starting and goal points are kept at or outside boundaries of a given finite domain, Kim and Khosla (1992), Daily and Bevly (2008), and Fahimi et al. (2008).

Local minimum is avoided, in case of both convex and concave obstacles, by adding a tangential velocity command to the repulsive velocity command, in the vicinity of obstacles, Bemporad, De Luca, and Oriolo (1996), Ogren and Leonard (2009), Zeng and Bone (2010), Necsulescu et al. (2012) and Necsulescu, Pruner, and Sasiadek (2014).
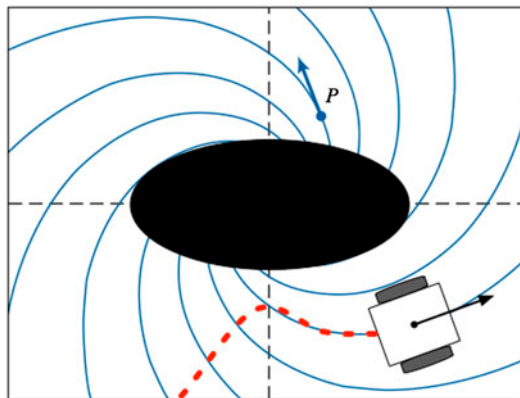

Figure 3. Combined source, sink, and uniform flow, Pruner (2013).

Simulations were carried out for the case of an environment in which obstacles are sensed locally in a dynamic window and result in local reactive control and collision avoidance approach, Necsulescu et al. (2012).

2.2. Superposition of elementary plane flows

Using the elementary hydrodynamics plane flow model, complex flows can be approximated by combining various elementary flows [2–7]. Source and uniform flow are described by the following stream function ψ and velocity potential function ϕ, respectively

$$\psi = -\frac{q}{2\pi}(\theta_2 - \theta_1) + Ur\sin\theta \tag{1}$$

$$\phi = \frac{q}{2\pi}\ln r\frac{r_2}{r_1} - Ur\cos\theta \tag{2}$$

while clockwise vortex and uniform flow are described by

$$\psi = \frac{K}{2\pi}\ln r + Ur\sin\theta \tag{3}$$

$$\phi = \frac{K}{2\pi}\theta - Ur\cos\theta \tag{4}$$

where r and θ are polar coordinates. The doublet of source and vortex is described by

$$\psi = -\frac{q}{2\pi}\theta - \frac{K}{2\pi}\ln r \tag{5}$$

$$\phi = \frac{q}{2\pi}\ln r - \frac{K}{2\pi}\theta \tag{6}$$

Figure 1 illustrates the flow in the case of combined source and vortex.

2.3. Mobile robot controller inspired by the hydrodynamics velocity potential flow theory

For a reactive navigation controller, velocity potential flow functions were implemented for two desired movements: the uniform flow to describe the flow of the vehicle toward the goal position and the attractive flow for travel at the maximum linear velocity set by the user. Figure 1 shows a differential drive mobile robot moving with the attractive flow toward the goal position.

Next, the spiral vortex (source and vortex) potential flow function is used to push the robot away and around obstacles. The path of the robot can be chosen along the flow lines of a spiral vortex, as it approaches the obstacle, and changes course to avoid collision [2–7].

The normal and tangential velocities of the robot, as it travels along the spiral vortex, can be calculated from the cylindrical velocity equations (Figure 2).

Figure 3 shows the flow characteristics for combined source, sink, and uniform flow. The velocity potential function ϕ for the spiral vortex is

$$\phi = -\frac{q}{2\pi}\ln r - \frac{K}{2\pi}\theta \tag{7}$$

By applying the cylindrical velocity equations from the normal and tangential velocities, U_n and U_t are calculated as

$$U_n = -\frac{q}{2\pi}\frac{1}{r} = -\frac{A}{r} \tag{8}$$

$$U_t = \frac{1}{r}\left(-\frac{K}{2\pi}\right) = -\frac{B}{r} \tag{9}$$

where A and B are constant parameters.

2.4. System parameters

When designing the algorithm for the reactive navigation controller with the velocity potential method, it was decided that the vehicle would flow toward the goal using a uniform flow field. The vehicle would travel on a straight line path from the initial position to the goal position. If the vehicle was not initially pointing at the goal, it would continue to travel at the same linear velocity, but would also rotate slowly until it points in the direction of the goal. When the vehicle enters the region of interest around the goal (dashed circle in Figure 4), it was designed to automatically slow down and then stop at the goal position.

Figure 4 shows the mobile robot velocity and angle parameters, the distance to the goal position, and the region of interest around the goal position. The robot parameters from Figure 4 are the following, Choset (2005):

Current position of the vehicle,
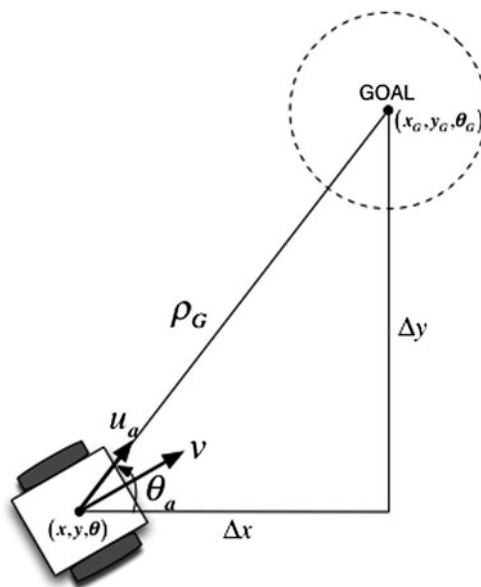
$$(x, y, \theta)$$

Figure 4.   Mobile robot parameters, Necsulescu et al. (2010).

Position of the goal,

$$(x_G, y_G, \theta_G)$$

Maximum linear and angular velocity (chosen by the user).

$\Delta\theta_a$ is defined as the difference between the desired angle and the current vehicle angle,

$$\Delta\theta_a = \theta_a - \theta \tag{10}$$

Figures 5 and 6 define robot obstacle avoidance parameters, Necsulescu et al. (2012) and Pruner (2013).

Distance from current position x, y, to the goal position x_G, y_G, shown in Figure 4, is defined by:

$$\rho_G = \sqrt{(x_G - x)^2 + (y_G - y)^2} \tag{11}$$

A function f is defined to slow down the vehicle and causes it to stop at the goal position when it enters the goal radius:
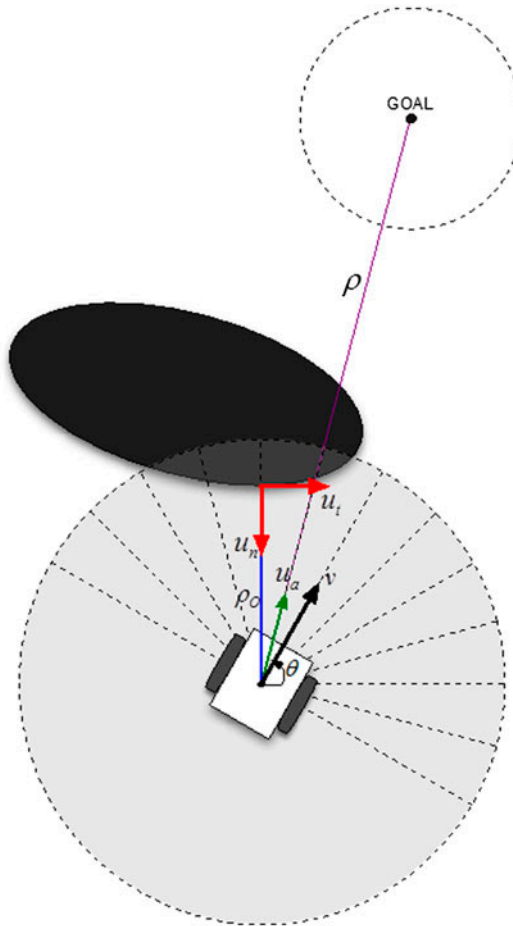

Figure 5.   Robot single obstacle avoidance, Necsulescu, Pruner, and Sasiadek (2013).

$$f(\rho_G, \rho_{GR}) = e^{-(\rho_G/\rho_{GR})} \tag{12}$$

where ρ_{GR} is the goal region radius (critical radius around the goal position). The magnitude of the normal and tangent vectors is a function of the shortest distance to the goal ρ_O.

$$|u_n| = |u_t| = \frac{1}{\rho_O} \tag{13}$$

The relation that slows down the vehicle close to the obstacle is the following exponential function:

$$f(\rho_O, \rho_{OR}) = e^{-(\rho_O/\rho_{OR})} \tag{14}$$

where ρ_{OR} is safety radius for the obstacle (within this radius, the vehicle will adjust its velocity to go around it).

Constant velocity command to move the robot toward the goal is given by:
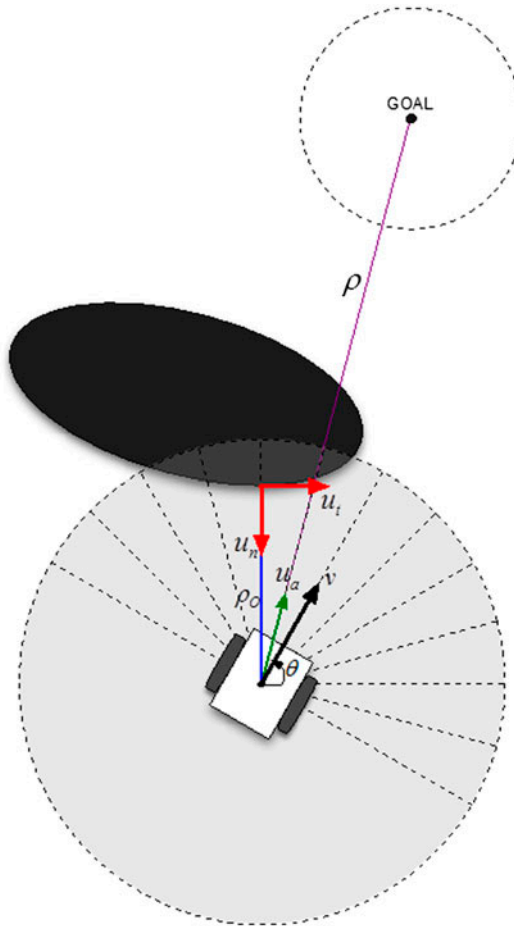
$$|u_a| = v_{max} \tag{15}$$

Figure 6.   Robot narrow passage collision avoidance, Pruner (2013).

where v_{max} is maximum cruising velocity of the robot. Obstacle angle is the angle associated with the shortest sensed distance. Normal and tangent vector angles are as follows:

$$\theta_n = \theta_O - \pi \tag{16}$$

$$\theta_t = \theta_n \pm \frac{\pi}{2} \tag{17}$$

Furthermore, the normal and tangent velocity command vectors are defined as:

$$u_n = u_n(\cos\theta_n + \mathrm{j}\sin\theta_n) \tag{18}$$

$$u_t = u_t(\cos\theta_t + \mathrm{j}\sin\theta_t) \tag{19}$$

Final velocity command vector v_r is obtained as a linear combination of the above velocities commands using the exponential function f to define their limits of application:
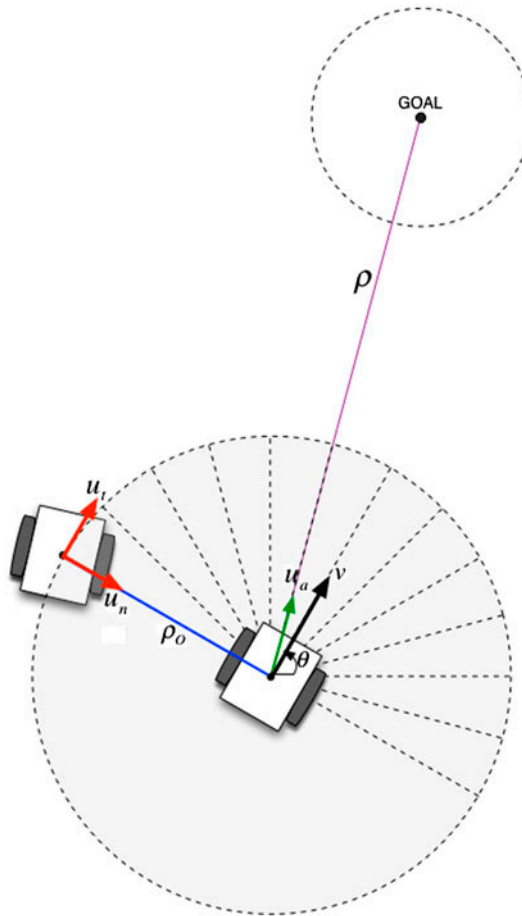

Figure 7.   Inter-robot collision avoidance.

$$v_r = k_a u_a (1 - f(\rho_G, \rho_{GR})) + k_n u_n (f(\rho_O, \rho_{OR})) + k_t u_t (f(\rho_O, \rho_{OR})) \tag{20}$$

The term $(1 - f(\rho_G, \rho_{GR})) = 1$ for $\rho_G \gg \rho_{GR}$. For example, for $\rho_G = 5\rho_{GR}, f(\rho_G, \rho_{GR}) = e^{-(5\rho_{GR}/\rho_{GR})}$ is approximately zero.

In this case, when no obstacle is detected, $f(\rho_O, \rho_{OR}) = 0$ and the robot is:

(1) Far from the goal, $(1 - f(\rho_G, \rho_{GR})) = 1$, such that

$$v_r = k_a u_a = v_{max} = \text{constant} \tag{21}$$

(1) Close to the goal, $\rho_G < \rho_{GR}, (1 - f(\rho_G, \rho_{GR}))$ decreases with ρ_G and $v_r = k_a u_a (1 - f(\rho_G, \rho_{GR}))$, and v_r decreases to zero and the robot stops at the goal.
(2) Near an obstacle, $\rho_O < \rho_{OR}$ and $f(\rho_O, \rho_{OR})$ increase toward 1. Max values are achieved at $\rho_O = \rho_{OR}$, where the normal and tangential velocities commands become

$$k_n u_n (f(\rho_O, \rho_{OR})) + k_t u_t (f(\rho_O, \rho_{OR})) \tag{22}$$

The attractive angular velocity command is calculated according to the equation:

$$\omega_a = k_a (1 - f(\rho_G, \rho_{GR})) \frac{\Delta\theta}{\Delta t} \tag{23}$$
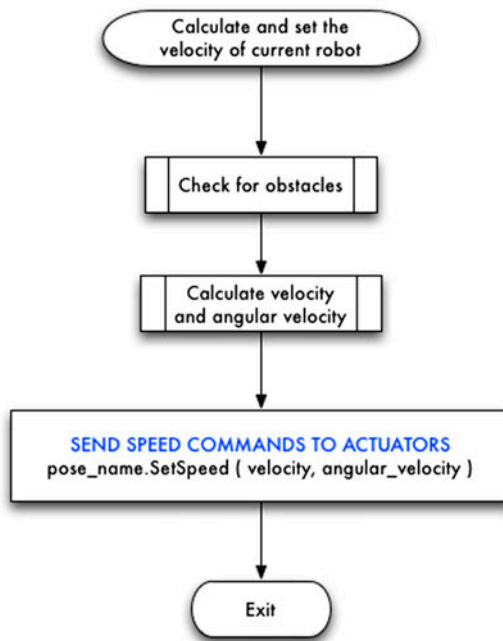

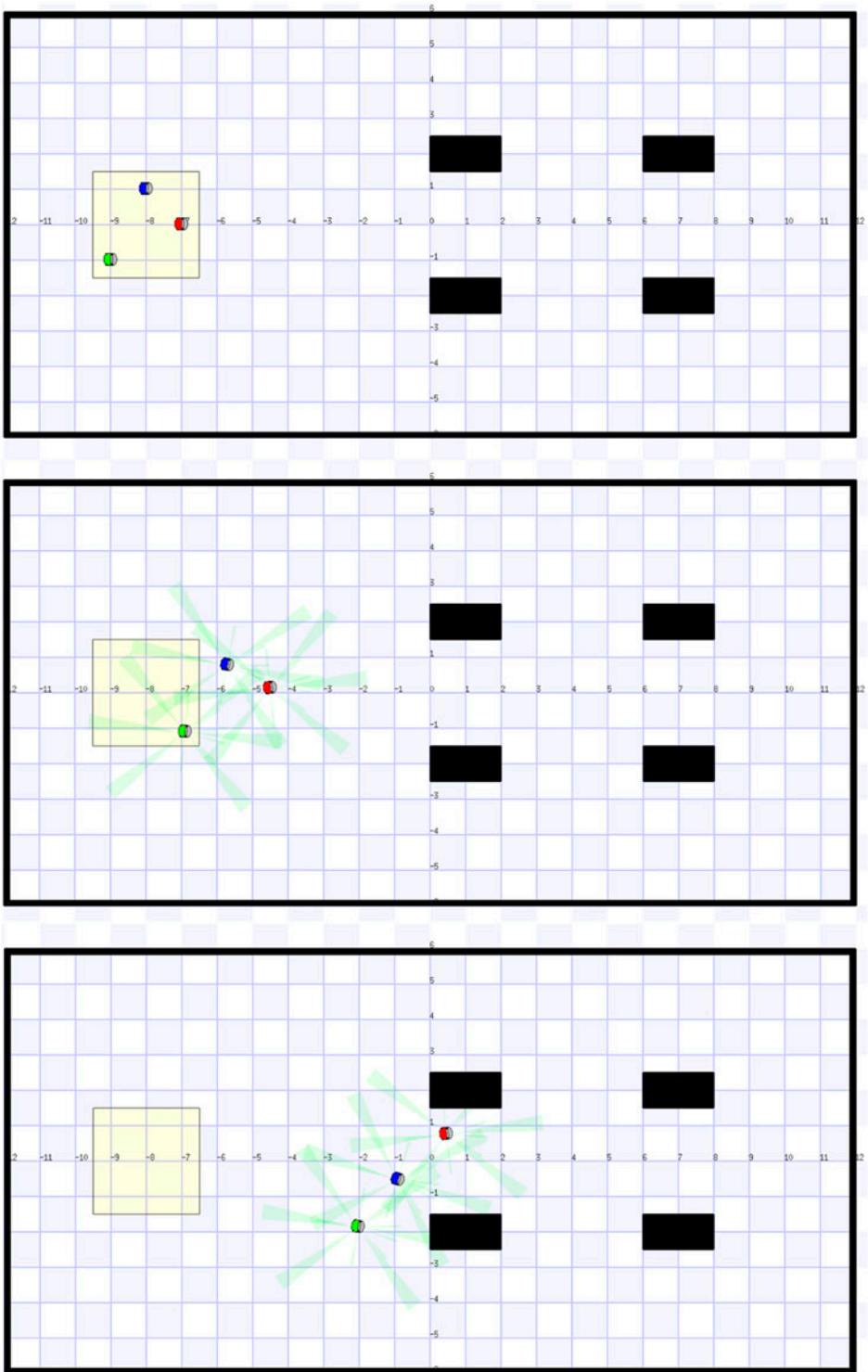Figure 8.   Velocity calculations, Pruner (2013).

Figure 9.   Simulation #1: material transfer of two pallets to lower left and one pallet at top right assembly stations.
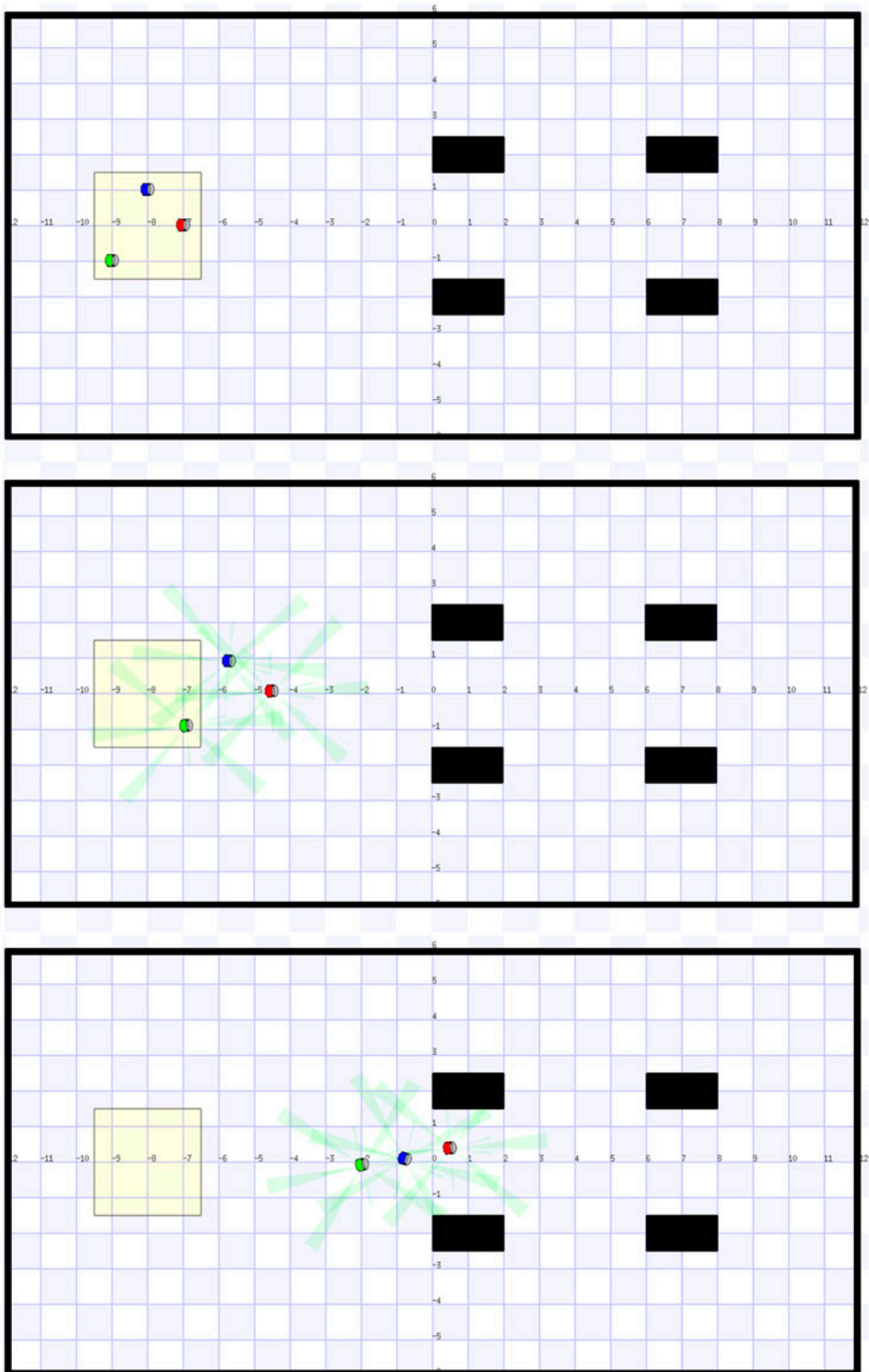
Figure 10.   Simulation #2: material transfer of two pallets to top right and one pallet at bottom left assembly stations.
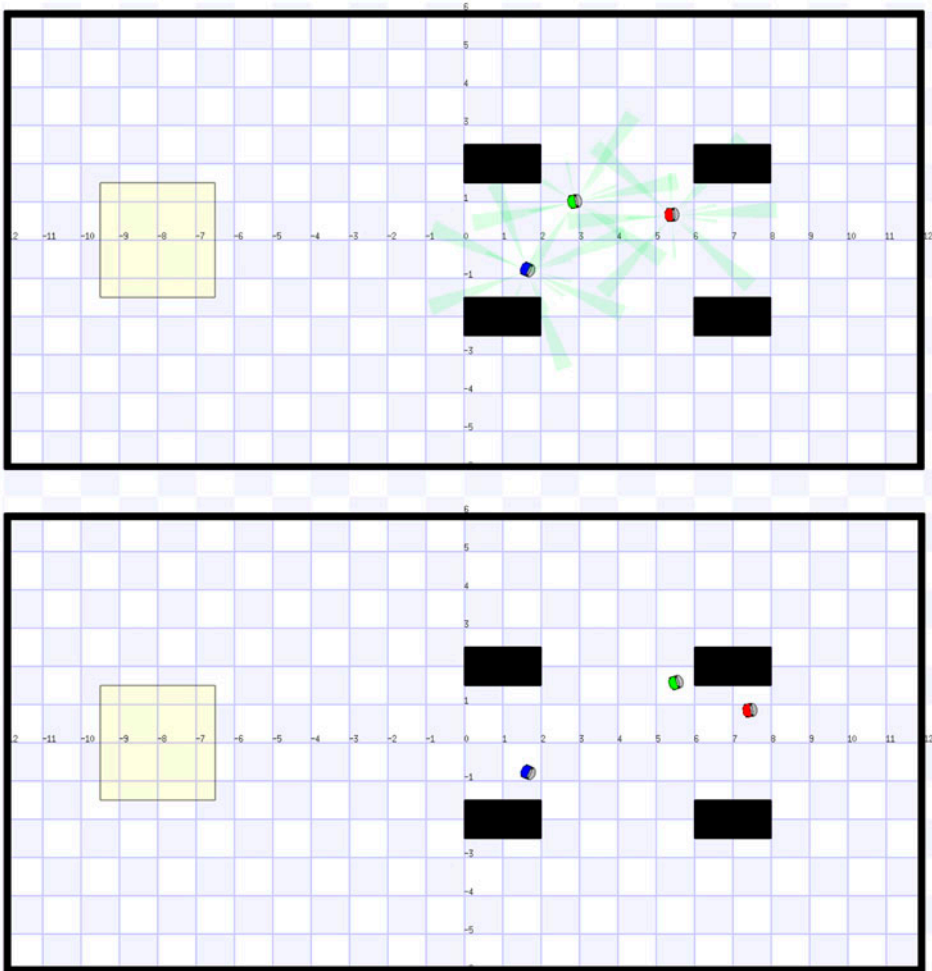
Figure 10.   (*Continued*)

where $\Delta\theta$ is the difference between the desired and actual heading and Δt is the desired time step.

Finally, the repulsive angular velocity command, given to the vehicle when an obstacle is in view, is found by:

$$\omega_o = k_o(f(\rho_O, \rho_{OR}))\frac{\Delta\theta_o}{\Delta t} \tag{24}$$

where

$$\omega_o = k_o(f(\rho_O, \rho_{OR}))\frac{\Delta\theta_o}{\Delta t} \tag{25}$$

where $\Delta\theta_o$ is the difference between the resultant angle, from the normal and tangent vectors, and the vehicles current heading.

Figure 11. Simulation #3: material transfer of three pallets to top right assembly station.

Figure 11.   (*Continued*).

Figure 12.   Block diagram of simulation program, Pruner (2013).

As in the cases for linear velocity, the function $(f(\rho_G, \rho_{GR}))$ causes the vehicle to slow down close to the goal, and the function and $(f(\rho_O, \rho_{OR}))$ increase the angular velocity magnitude as the vehicle moves closer toward an obstacle.

$$\omega_o = k_o(f(\rho_O, \rho_{OR}))\frac{\Delta\theta_o}{\Delta t} \tag{26}$$

where $\Delta\theta_o$ is the difference between the resultant angle, from the normal and tangent vectors, and the vehicles current heading.
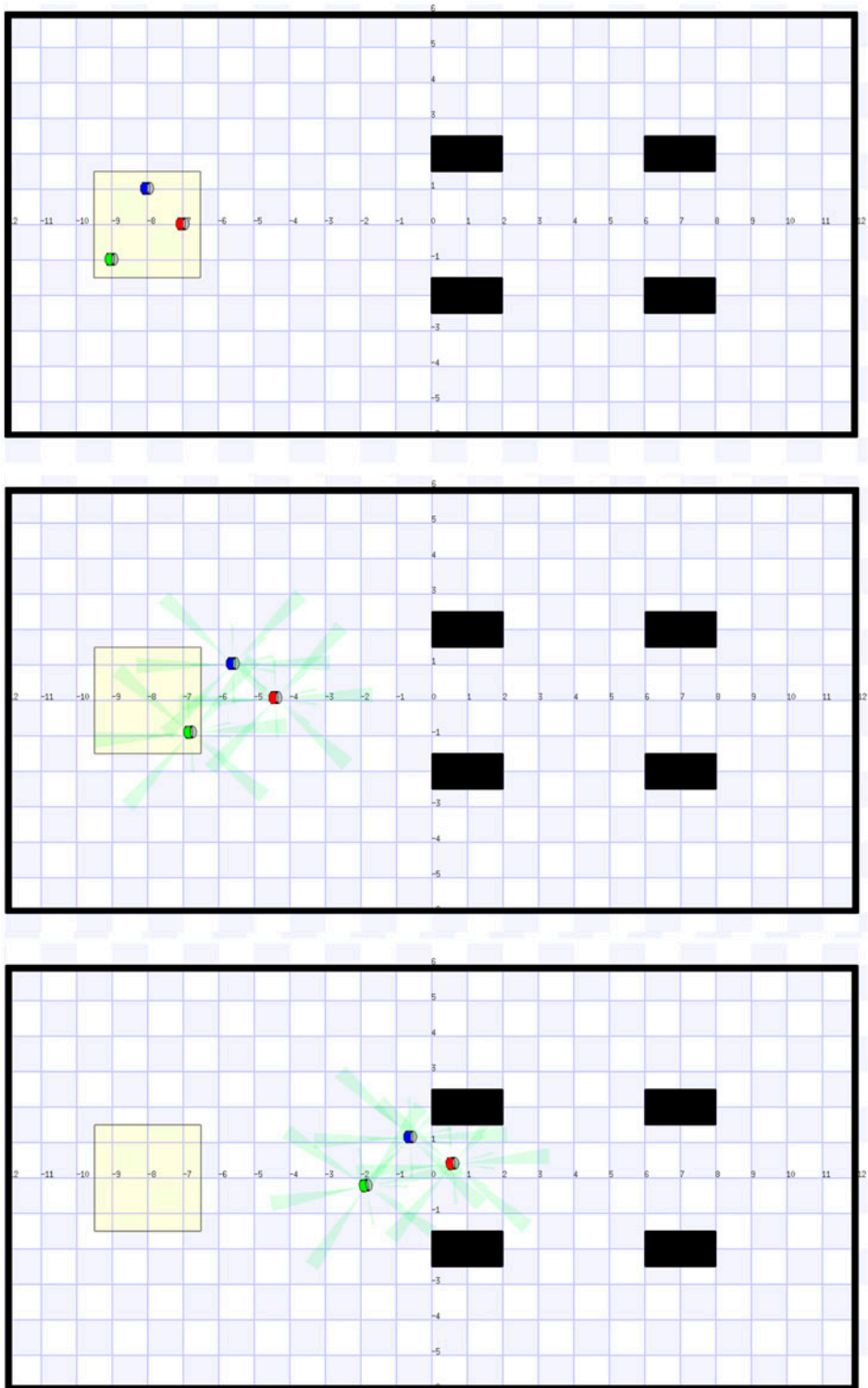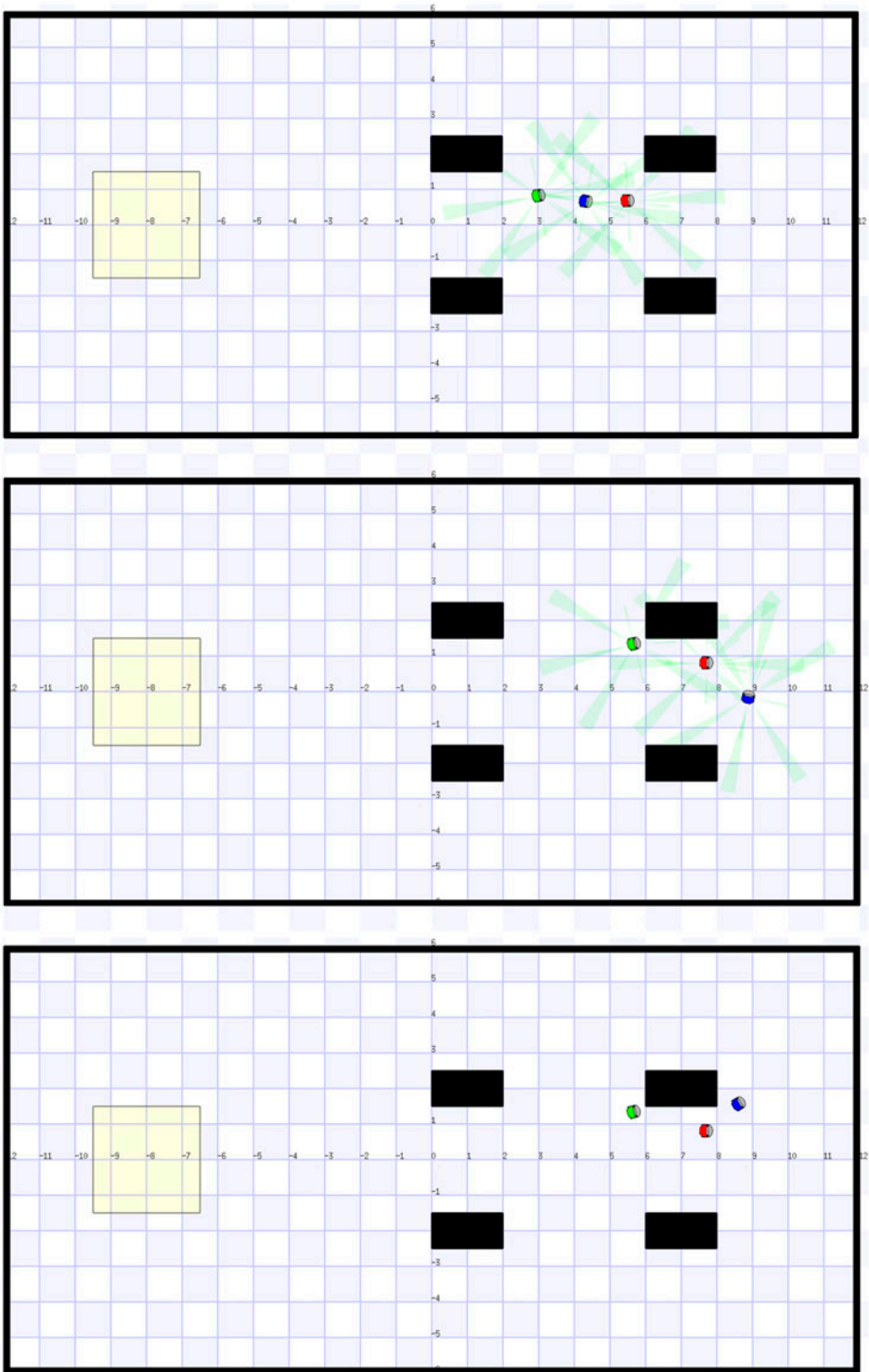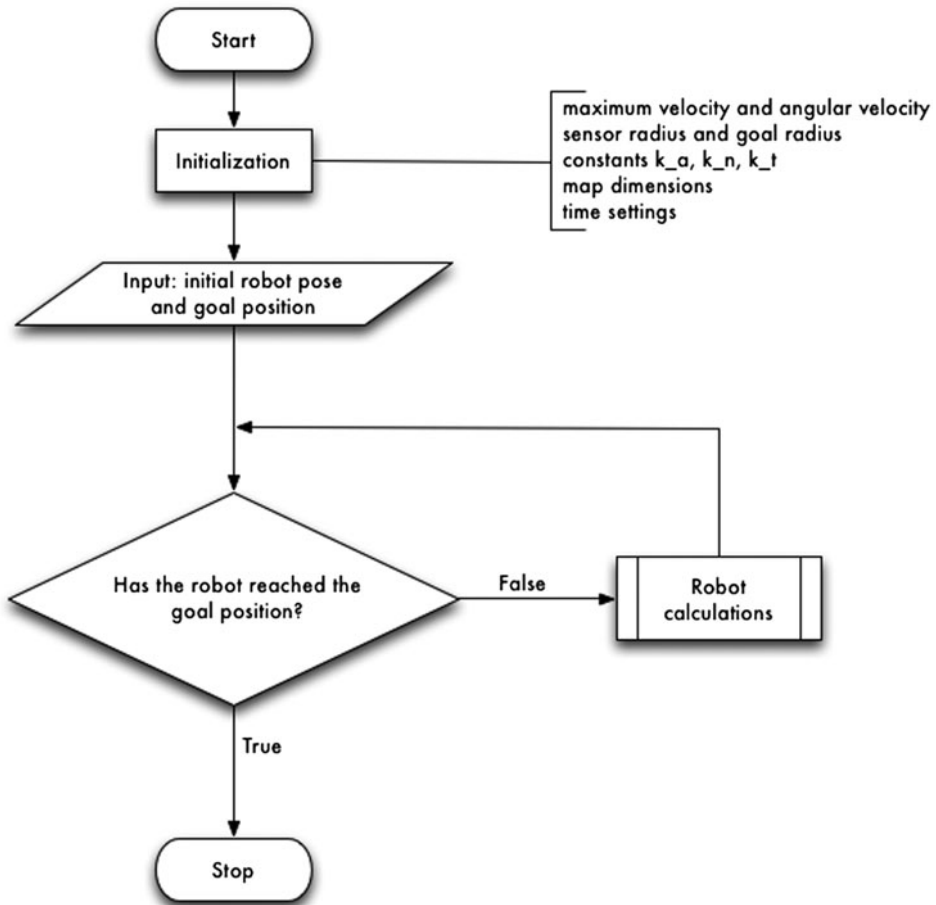
As in the cases for linear velocity, the function $(f(\rho_G, \rho_{GR}))$ causes the vehicle to slow down close to the goal, and the function and $(f(\rho_O, \rho_{OR}))$ increase the angular velocity magnitude as the vehicle moves closer toward an obstacle.

3.   Simulation algorithm

PlayerProxies[TM] was used to connect the robots to the PC over a wireless network. Figure 7 shows the parameters for the case that a robot touches the safety circle of
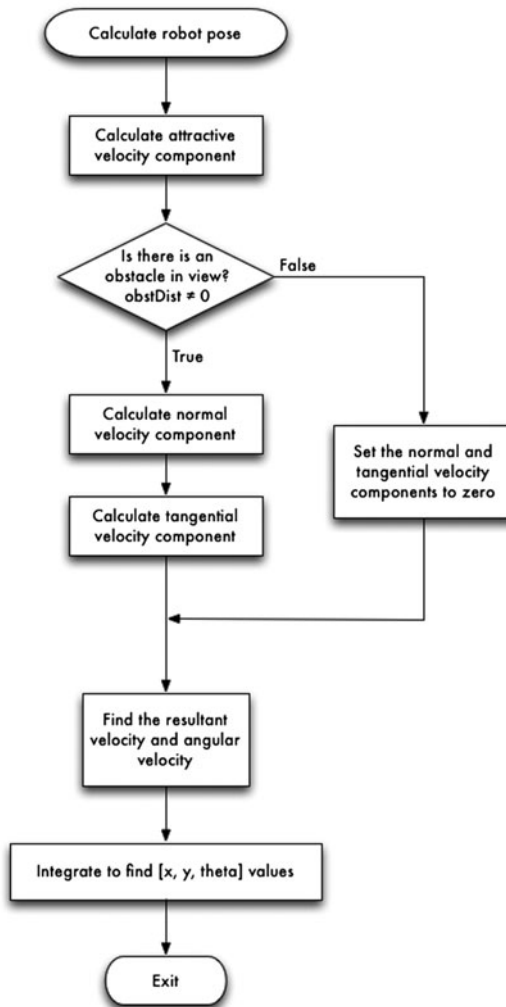
Figure 13.   Block diagram of robot velocity commands calculation to avoid collisions and arrive at the desired position, Pruner (2013).

radius of another robot ρ_o and the velocity commands v_n and v_t that result in collision avoidance. The simulation program calculates and sets the velocities of all the team members in a loop until one of the robots reaches the goal position. Figure 8 shows how the controller sets the proxies for any number of robots and the instruction to obtain x, y, and θ, Pruner (2013).

The velocity calculations, shown in Figure 8, are looped until each robot calculation is carried out. When obstacles are sensed, ρ_a and θ_0 are measured, and U_n and U_t are calculated with equations 18, 22, and 23. Velocity commands for v_0, v_r, and ω_r from equations 26–28 are set, and when a robot has reached the goal position, all of the vehicles are stopped and the simulation ends.

Simulations and experiments using the velocity potential controller were carried out in MATLAB^{TM} and Player/Stage^{TM}.
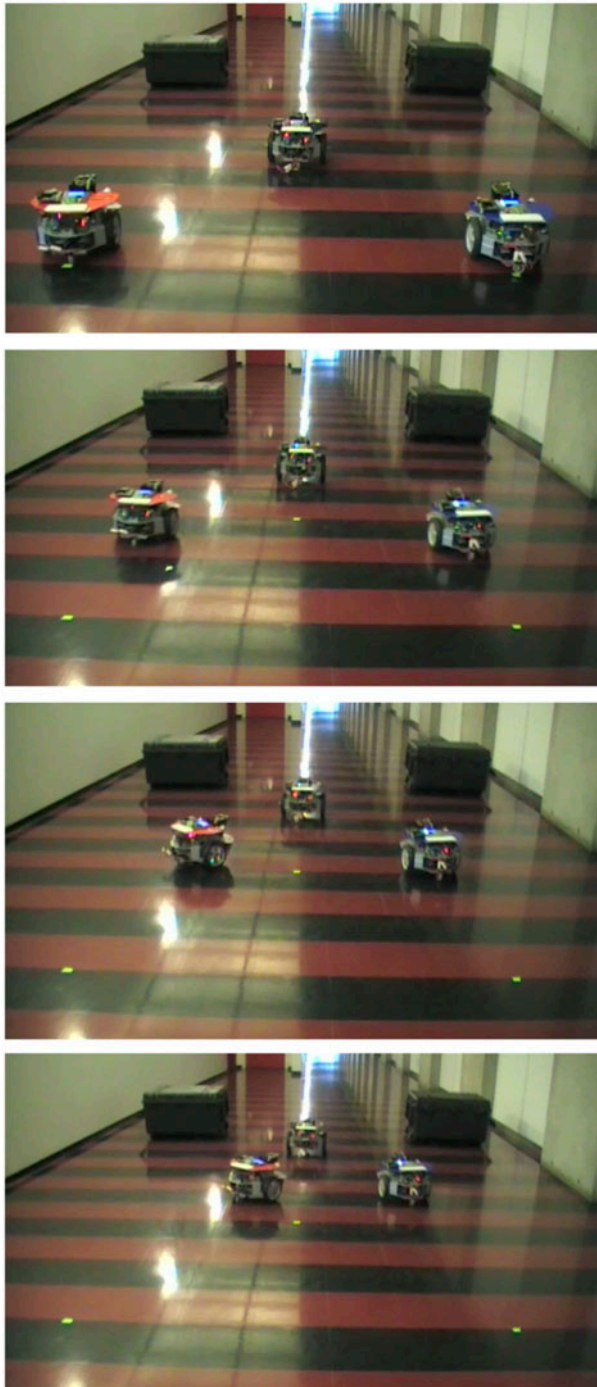
Figure 14. Experimental results for a self-organizing formation of autonomous mobile robots negotiating a narrow passage among assembly stations.

Figure 14.   (*Continued*).

4.   Simulation results

Simulations were carried out for three scenarios regarding material transfer to assembly stations. These scenarios were chosen to justify the claim that a formation of autonomous mobile robots has a high flexibility in serving the workstations using the same robots.

Figure 9 shows the results for the simulation of material transfer of two pallets to lower left and one pallet at top right assembly stations, Figure 10 material transfer to top right and one pallet at bottom left assembly stations, and Figure 11 for material transfer of three pallets to top right assembly station.

These simulation results confirm that the proposed control scheme permits to achieve the intended pallets transfer to various assembly stations, while avoiding collisions with other assembly stations and among moving robots. The approach tested in these simulations can be considered a new solution for serving several workstations in conditions of a dynamically changing environment, unknown in advance. The approach uses a proposed sense and control method based on velocity potential fields, which is free from stopping in a local equilibrium point away from the goal. The approach provides significant flexibility to formations of mobile robots when compared with autonomous guided vehicles.

5.   Experimental results

Experiments were carried out for a self-organizing formation of autonomous mobile robots negotiating a narrow passage among assembly stations, using the block diagrams from Figures 12 and 13. The preliminary results shown in Figure 14 confirm the validity of the proposed control scheme and of the simulation results. Further experimental study will be carried out to test experimentally a variety of scenarios for material handling by a formation of self-organizing autonomous robots.

6.   Conclusions

The use of autonomous formations of autonomous multi-vehicle in material handling applications is justified by the ability to perform such tasks with great efficiency, significant improvement in flexibility, and robustness. Multi-vehicle systems require a large degree of organization in order to work effectively, and formations are often used to

deliver an appropriate coordination strategy. Self-organizing formations can be a valuable candidate for this purpose.

The results presented in this paper show that the proposed control scheme using velocity potential approach for self-organized formation in the presence of obstacles achieves the proposed tasks and represents a potentially more flexible alternative to automated guided vehicles following fixed traces. The proposed approach was developed for unknown environments. Further developments of the approach are needed for the case of known or partly known environments.

Future research is justified for mobile robots equipped with programmable manipulators to replace current simple and rigidly predefined material transfer devices.

References

Antonelliet, G., Arrichello, F., & Chiaverini, S. (2009). Experiments of formation control with multirobot systems using the null-space-behavioural control. *IEEE Transactions on Control Systems Technology, 17*, 1173–1182.

Arkin, R. C., & Murphy, R. R. (1990). Autonomous navigation in a manufacturing environment. *IEEE Transactions on Robotics and Automation, 6*, 445–454.

Bahceci, E., Soysal, O., & Sahin, E. (2003). *A review: Pattern formation and adaptation in multi-robot systems* (Technical Report, CMU-RI-TR-2003-43). Pittsburgh, PA: Carnegie Mellon University, Robotics Institute.

Bemporad, A., De Luca, A., & Oriolo, G. (1996). Local incremental planning for a car-like robot navigation among obstacles. *IEEE International Conference on Robotics and Automation, 2*, 1205–1211.

Bischoff, R., Kurth, J., Schreibe, G., & Koeppe, R. (2010). *The KUKA-DLR lightweight robot arm – A new reference platform for robotics research and manufacturing* (pp. 1–8). International Symposium on an Robotics (ISR), 2010 6th German Conference on Robotics (ROBOTIK), June 2010.

Choset, H. (2005). *Principles of robot motion: Theory, algorithms, and implementations.* Cambridge, MA: The MIT Press.

Daigle, M. J., Koutsoukos, X. D., & Biswas, G. (2007). Distributed diagnosis in formations of mobile robots. *IEEE Transactions on Robotics, 23*, 353–369.

Daily, R. & Bevly, D. (2008). *Harmonic potential field path planning for high speed vehicles* (pp. 4609–4614). American Control Conference 2008, Washington, DC.

Eghtesad, M., & Necsulescu, D. (2006). Study of the international dynamics of an autonomous mobile robot. In *Robotics and autonomous systems* (pp. 342–349). Elsevier.

Fahimi, F., Nataraj, C., & Ashrafiuon, H. (2008). Real-time obstacle avoidance for multiple robots. *Robotica, 27*, 189–198.

Fierro, R., & Song, P. (2005). Coordination of robot teams: A decentralized approach in Current trends in nonlinear systems and control: In honor of Kokotovic and T Nicosia. In L. Menini, et al. (Eds.), *Systems & Control: Foundations & Applications* (pp. 347–363). Birkhauser.

Fierro, R., Song, P., Das, A., & Kumar, V. (2002). Cooperative control of robot formations. In R. Murphey & P. Pardalos (Eds.), Cooperative control and optimization (Vol. 66, pp. 73–93, Chap. 5). Applied optimization. Kluwer Academic Press.

Fisher, K. (1999). Agent-based design of holonic manufacturing systems. *Robotics and Autonomous Systems, 27*, 3–13.

Hu, H., & Brady, M. (1997). Dynamic global path planning with uncertainty for mobile robots in manufacturing. *IEEE Transactions on Robotics and Automation, 13*, 760–767.

Hu, H., & Gu, D. (1999). *Landmark-based navigation of mobile robots in manufacturing, 1999.* (Vol. 1, pp. 121–128). Proceedings ETFA '99. 1999 7th IEEE International Conference on Emerging Technologies and Factory Automation, 18 October 1999–21 October 1999.

Jaydev, D., Desai, J. P., Ostrwski, J., & Kumar, V. (1998). Controlling formations of multiple mobile robots. *Proceedings of the IEEE International Conference on Robotics and Automation, 4*, 2864–2869.

Kim, J.-O., & Khosla, P. (1992). Real-time obstacle avoidance using harmonic potential functions. *IEEE Transaction on Robotics and Automation, 8*, 338–349.

Kupec, T. (1989). Integration of autonomous, mobile robots in flexible manufacturing systems. In *Proceedings of the International Conference on Intelligent Autonomous systems* (pp. 122–133). Amsterdam: IOS Press.

Li, X., & Xiao, J. (2005). Robot formation control in leader-follower motion using direct lyapunov method. *International Journal of Intelligent Control and Systems, 10*, 244–250.

Mastellone, S., Stipanovici, D. M., Grauke, C. R., Intlekofer, K., & Spong, M. (2008). Formation control and collision avoidance for multi-agent non-holonomic systems: Theory and experiments. *The International Journal of Robotics Research, 27*, 107–126.

Moshtagh, N., Nathan, M., Jadbabaie, A., & Danilidis, K. (2009). Vision-based distributed control laws for motion coordination of nonholonomic robots. *IEEE Transactions on Robotics, 25*, 581–860.

Nathan, M., & Kumar, V. (1998). *Controlling shapes of ensembles of robots of finite size with Nonholonomic constraints* (pp.2864–2869). ICRA Conference, Leuven, Belgium.

Necsulescu, D., Pruner, E., Sasiadek, J., & Kim, B. (2010). *Control of nonholonomic autonomous vehicles and their formations* (pp. 37–42). IFAC/IEEE 15th International Conference on Methods and Models in Automation and Robotics MMAR, 23–26 August, Międzyzdroje.

Necsulescu, D., Pruner, E., Kim, B., & Sasiadek, J. (2012). *Decentralized control of autonomous mobile robots formations using velocity potentials*. 2nd IFAC Workshop on Multivehicle Systems, 3–5 October, Espoo, Finland.

Necsulescu, D., Pruner, E., & Sasiadek, J. (2013). *Control of self-organizing formations autonomous agents using velocity potential fields for material transfer*. IMS 2013 – 11th IFAC Workshop on Intelligent Manufacturing Systems, May 22–24, 2013, Sao Paulo, Brazil.

Necsulescu, D., Pruner, E., & Sasiadek, J. (2014), *Self-organizing formations control for large number of autonomous mobile robots*. The 33rd IASTED International Conference on, Identification and Control, MIC 2014, February 17–19, 2014, Innsbruck, Austria.

Ogren, P., & Leonard, N. (2009). *A convergent dynamic window approach to obstacle avoidance* (pp. 1–8). IEEE Transactions on Robotics 2005, New York.

Pruner, E. (2013). *Control of self-organizing and geometric formations* (M.A. Sc. thesis). University of Ottawa, Canada.

Roberti, F., Rosales, A., Scaglia, G., Mut, V., & di Sciascio, F. (2009). Formation control for a team of wheeled mobile robots. *Robotica, 27*, 1–12.

Siegwart, R., Nourbakhsh, I. R., & Scaramuzza, D. (2011). *Introduction to autonomous robots*. Boston: MIT Press.

Uny Cao, Y. (1997). Cooperative mobile robotics: Antecedents and directions. *Journal of Autonomous Robots, 4*, 7–27.

Yamada, Y., Ookoudo, K., & Komura, Y. (2003). Layout optimization of manufacturing cells and allocation optimization of transport robots in reconfigurable manufacturing systems using particle swarm optimization. *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, 2*, 2049–2054.

Yamashita, A., Fukuki, M., Ota, J., & Arai, T. (2000). Motion planning for cooperative transportation of a large object by multiple mobile robots in a 3D environment. *Proceedings. ICRA '00. IEEE International Conference on Robotics and Automation, 4*, 3144–3151.

Yamashita, A., Arai, T., Ota, J., & Asama, H. (2003). Motion planning of multiple mobile robots for cooperative manipulation and transportation. *IEEE Transactions on Robotics and Automation, 19*, 223–237.

Zeng, L., & Bone, G. (2010). *Collision avoidance for nonholonomic mobile robots among unpredictable dynamic obstacles including humans* (pp. 940–947). 6th annual IEEE Conference on Science and Engineering, Toronto, Canada.