Motion Coordination in a Busy Environment: Robots Accompanying People

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Abstract

In this paper, we consider the problem of moving a formation of two objects, the leader and the accompanying wing man, through a natural busy environment. The intended motion of the leader is not explicitly communicated to the wing man. We allow a disturbance of the formation by other stationary or moving objects. The approach described in the paper is based on a method for motion planning amongst moving obstacles known as Velocity Obstacle approach. We extend this method by a method for tracking a virtual target which allows us to vary the wing man's heading and velocity with the locomotion of the leader and the state of the mission area. In our experiments the leader was a human person, moving at walking speed. The wing man was a mobile robot, more precisely a robotic wheelchair, which was supposed to accompany the human person in a certain relative position. The tests were conducted in the concourse of a railway station at regular business hours.

1 Introduction

We consider the problem of moving a formation of several individual moving objects through a natural busy environment. A formation usually consists of a leader and a number of wing men, who accompany the leader by maintaining a certain relative position with respect to the leader and its heading during locomotion. The prime motion of the formation is determined by the motion of the leader. Unlike in military applications this prime motion of the leader is not known to the wing men in advance nor is it communicated explicitly, for example, by a command. Rather than being informed about the leaders future motion each wing man is expected to observe the motion of the leader and adjust its own motion appropriately. As mentioned above, we further assume that the formation moves through a busy environment which is populated by other stationary or moving objects. With this assumption, we have to allow a disturbance of the formation by other objects.

The approach described in the paper is based on a method for motion planning amongst moving obstacles known as Velocity Obstacle approach. We extend this method by a method for tracking a virtual target which allows us to vary the wing men's heading and velocity with the locomotion of the leader and the state of the mission area.

As prime application of this approach we consider a scenario where the leader is a human person and the wing man is a robot moving with the human through a busy, public environment. More precisely, the robot is a robotic wheelchair, which is supposed to accompany the human person in a certain relative position through this busy environment (see also [3, 4]). In our experiments, the busy environment was the concourse of the railway station in Ulm, Germany, which has become our favorite test field.

This scenario has a very useful application in the transportation of disabled or elderly people or the transportation of patients in a hospital. Transportation services are usually carried out by nursing personnel which pushes the patient or disabled person sitting or lying in some type of carriage, for example a wheelchair. Since pushing and maneuvering a heavy carriage exposes the back of the pushing person to significant strain, these people often suffer severe long-term back problems. Using a robotic wheelchair, which is able to follow the nurse side by side, through busy hospital hallways would certainly allow the reduction or even avoid this problem.

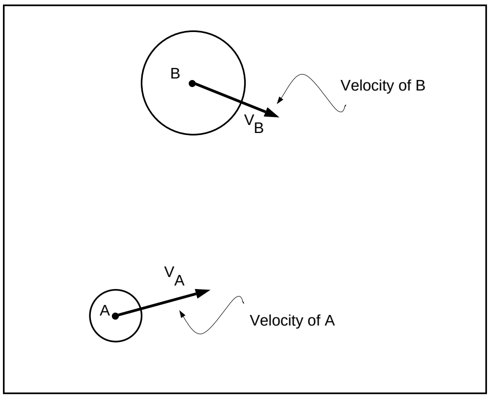
2 Moving in Formation Through a Busy Environment

For maintaining the relative position to a leader during locomotion the control system of each wing man employs a three layer control architecture. The layer for elementary motion control is at the bottom of this architecture. This layer offers two control modes, a mode for velocity control [1] and a mode for position control.

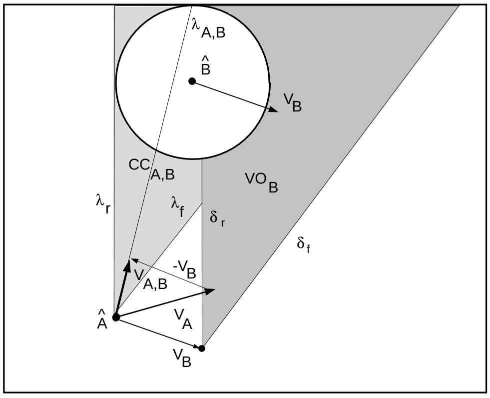
The layer for elementary motion control receives its input from the layer for *tactical navigation*, which computes a collision-free course to a target position in an environment which stationary as well as moving objects. This layer is based on the *Velocity Obstacle* approach [2, 6] which is summarized in the following section.

The Velocity Obstacle approach assumes a target velocity and heading, which in the case of an unobstructed path leads to the target location. In the case of obstacles the approach computes an actual velocity and heading, which ensure a collision-free locomotion. These actual values may deviate from the target values. They are selected, however, such that they minimize this deviation from the target velocity and heading.

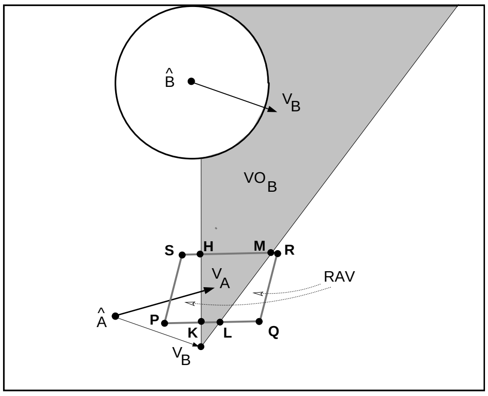
The tactical navigation layer is fed by the top layer which we called the *Virtual Target Tracking*. By defining a relative position of the wing man with respect to the leader and by deriving proper target velocities and headings in order to maintain this relative position while both leader and wing man are moving, this top layer creates the desired formation.



a) objects on collision course



b) velocity obstacle VO



c) reachable avoidance velocities

Figure 1: The *Velocity Obstacle* approach

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[1] More specifically, velocity control applies to both the translational and rotational velocity (v, ω)

2.1 Velocity Obstacles

To introduce the Velocity Obstacle (VO) concept, we consider the two circular objects, A and B, shown in Figure 1a at time t_0, with velocities $\mathbf{v}_A$ and $\mathbf{v}_B$. Let circle A represent the steered vehicle, and circle B represent an obstacle. To compute the VO, we first map B into the *Configuration Space* of A, by reducing A to the point $\widehat{A}$ and enlarging B by the radius of A to $\widehat{B}$, and represent the state of the moving object by its position and a velocity vector attached to its center. Then, the set of colliding *relative* velocities between $\widehat{A}$ and $\widehat{B}$, called the *Collision Cone*, $CC_{A,B}$, is defined as $CC_{A,B} = \{\mathbf{v}_{A,B} \mid \lambda_{A,B} \cap \widehat{B} \neq \emptyset\}$, where $\mathbf{v}_{A,B}$ is the relative velocity of $\widehat{A}$ with respect to $\widehat{B}$, $\mathbf{v}_{A,B} = \mathbf{v}_A - \mathbf{v}_B$, and $\lambda_{A,B}$ is the line of $\mathbf{v}_{A,B}$. This cone is the light grey sector with apex in $\widehat{A}$, bounded by the two tangents λ_f and λ_r from $\widehat{A}$ to $\widehat{B}$, shown in Figure 1b. Any relative velocity that lies between the two tangents to $\widehat{B}$, λ_f and λ_r, will cause a collision between A and B. Clearly, any relative velocity outside $CC_{A,B}$ is guaranteed to be collision-free, provided that the obstacle $\widehat{B}$ maintains its current shape.

The collision cone is specific to a particular pair of steered vehicle/obstacle. To consider multiple obstacles, it is useful to establish an equivalent condition on the *absolute* velocities of A. This is done simply by adding the velocity of B, $\mathbf{v}_B$, to each velocity in $CC_{A,B}$ and forming the *Velocity Obstacle* VO_B, $VO_B = CC_{A,B} \oplus \mathbf{v}_B$ where $\oplus$ is the Minkowski vector sum operator, as shown in Figure 1b by the dark grey sector. The VO partitions the absolute velocities of A into *avoiding* and *colliding* velocities. Selecting $\mathbf{v}_A$ outside of VO_B would avoid collision with B. Velocities on the boundaries of VO_B would result in A grazing B.

To avoid multiple obstacles, we consider the union of the individual velocity obstacles, $VO = \cup_{i=1}^{m} VO_{B_i}$, where m is the number of obstacles. The avoidance velocities, then, consist of those velocities $\mathbf{v}_A$, that are outside all the VO's.

An *avoidance maneuver* consists of a one-step change in velocity to avoid a future collision within a given time horizon. The new velocity must be achievable by the steered vehicle, thus the set of avoidance velocities is limited to those velocities that are physically reachable by vehicle A at a given state over a given interval. This set of *reachable velocities* is represented schematically by the polygon $PQRS$ shown in Figure 1c. The set of *reachable avoidance velocities*, RAV, is defined as the difference between the reachable velocities and the velocity obstacle. A maneuver avoiding obstacle B can then be computed by selecting any velocity in RAV. Figure 1c shows schematically the set RAV consisting of two disjoint subsets. For multiple obstacles, the RAV may consist of multiple disjoint subsets.

It is possible then to choose the type of an avoidance maneuver, by selecting on which side of the obstacle the steered vehicle will pass. As discussed earlier, the boundary of the velocity obstacle VO, $\{\delta_f, \delta_r\}$, represents all absolute velocities generating trajectories tangent to $\widehat{B}$, since their corresponding relative velocities lay on λ_f and λ_r. For example, the only tangent velocities in Figure Figure 1c are represented by the segments KH and LM of the reachable avoidance velocity set RAV. By choosing velocities in the set $PKHS$ or $MLQR$, we ensure that the corresponding avoidance maneuver will avoid the obstacle from the rear, or the front, respectively.

2.2 Motion Coordination By Tracking a Virtual Moving Target

Let us consider two moving objects L and W. To coordinate the motion of both objects such that one object "accompanies" the other in a formation requires to control the relative position of the wing man W with respect to the accompanied leader L during locomotion. We describe this desired relative position of the wing man with respect to the accompanied leader by a vector $p_L - p_W$, where p_L and p_W are the positions of the leader and the wing man, respectively. Alternatively the desired relative position can be described by a lateral distance d_L and an advance distance d_A.

What does maintaining the relative position between the accompanying and the accompanied object now mean in detail? As the wing man's observation takes place only at discrete time steps, let us consider the problem at such a discrete time step t (see Figure 2). At t the wing man observes the leader at a position $p_L(t)$. From its previous observation(s) the wing man knows, that the leader was at position $p_L(t-\Delta t)$ at time $t-\Delta t$. This allows the wing man to infer the leader's velocity $v_L(t)$ at time t with $v_L(t) = (\ p_L(t) - p_L(t-\Delta t)\ )/\Delta t$. Note that in our definition velocity is a vector which comprises magnitude and direction of the velocity. Informally we speak about the leaders's velocity and heading.

Let us now assume for a moment that the wing man at t has reached the desired relative position with respect to the actual position of the accompanied leader. We denote this position as $\tilde{p}_W(t)$. In order to maintain this desired relative position during its locomotion the wing man needs to know the leader's future velocity and heading, from which it can compute the velocity and heading taking it to this desired relative position in the future. We view this desired future relative position $\tilde{p}_W(t+\Delta t)$ as *virtual target* which moves with the accompanied leader, hence the term *virtual moving target*.

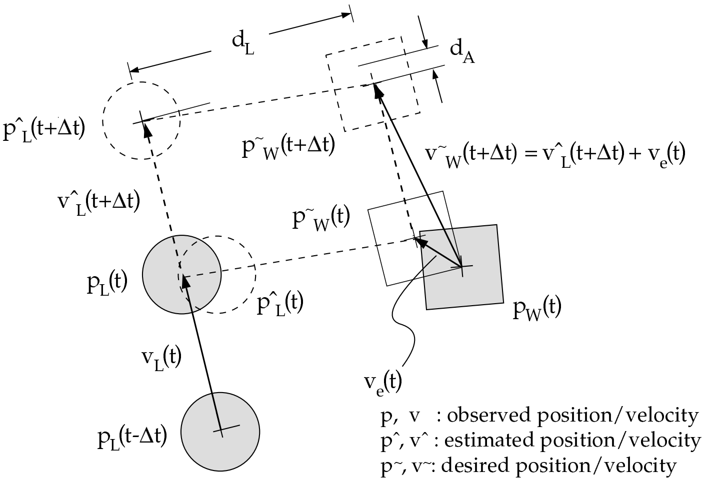


Figure 2: Moving in a formation by tracking a virtual moving target

The apparent problem is to estimate this future velocity and heading of the accompanied leader. Sophisticated methods for estimating the velocity and heading of a moving object are described in [1, 5]. However, as the accurate prediction of the motion of a leader through a busy, natural environment, which underlies continuos as well as spontaneous changes, is a difficult and often vain venture in practice, we content ourselves with a very coarse estimate. We simply extrapolate the leader's past velocity $v_H(t)$ and take it as an estimate of the leader's future velocity $\hat{v}_L(t+\Delta t)$. With $\hat{v}_L(t+\Delta t)$ we also obtain an estimate of the leader's position at time $t+\Delta t$, $\hat{p}_L(t+\Delta t)$. This makes it straightforward to determine the desired position of the wing man, $\tilde{p}_W(t+\Delta t)$, at time $t+\Delta t$ (see Figure 2).

At the beginning of the above considerations we assumed that at time t the wing man has reached the desired relative position $\tilde{p}_W(t)$ with respect to the accompanied leader. Apparently this assumption describes an ideal situation. For a number of reasons it is very unlikely, however, that the wing man has really reached the desired position. Firstly, the wing man's locomotion towards its virtual target may be perturbated by stationary or moving obstacles in the environment. So the wing man may have to deviate from the desired velocity $\tilde{v}_W(t+\Delta t)$. We discuss this issue in the following section. Secondly, the estimate of the leader's future velocity and position, which we used to determine the wing man's desired velocity, will be inaccurate. The wing man will not notice this before it makes its next observation at time $t+\Delta t$. Finally, the wing man's velocity control is afflicted with a certain delay, which also results in a positional error.

All these reasons together make it very likely that the wing man, when it senses its own position and the position of the accompanying leader at time t, will discover that its true position $p_R(t)$ deviates noticeably from the desired position $\tilde{p}_W(t)$, which is determined by the leader's true position

$p_H(t)$ and the offset by the lateral and advance distance, d_L and d_A, respectively. To compensate for this positional error we have to add a velocity vector $v_e(t)$ to the vector $\hat{v}_L(t+\Delta t) = v_H(t)$, which would be the wing man's desired velocity in the ideal case. With that the corrected desired velocity for the wing man becomes $\tilde{v}_W(t+\Delta t) = \hat{v}_L(t+\Delta t) + v_e(t)$. Note that we implicitly assume that the time interval Δt is constant.

2.3 Combining the Velocity Obstacle Approach with Virtual Target Tracking

The velocity $\tilde{v}_W(t+\Delta t)$ is the input to the control layer which computes the Velocity Obstacles and determines a collision-free course for the wing man. This velocity in the ideal case of an unobstructed environment takes the wing man to the desired relative position with respect to the accompanied leader and thereby leads to the desired formation. In the following we briefly discuss this combination of the Velocity Obstacle approach with the Virtual Target Tracking approach and its effects in an unobstructed environment.

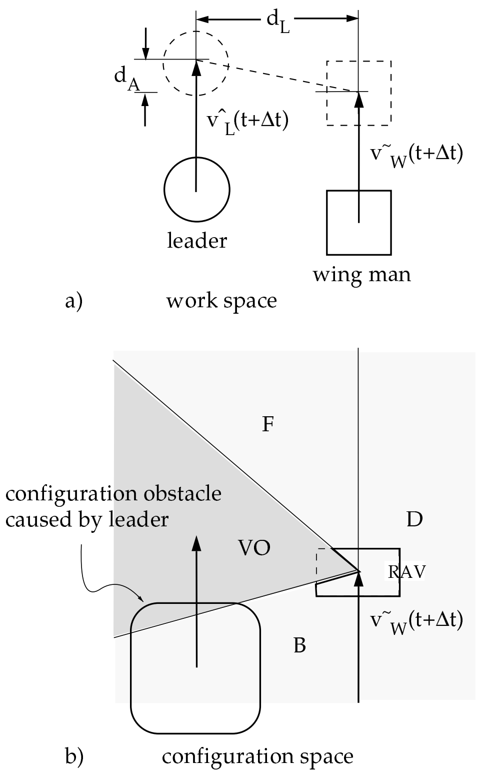


Figure 3: Combining the Velocity Obstacle Approach with virtual target tracking

Figure 3a shows the wing man and the leader moving an ideal unobstructed environment. As a result of the prediction of the leader's future motion and the computation of the desired future relative position of the wing man we obtain $\tilde{v}_W(t+\Delta t)$ as described above. At this point we do not care about the conditions of the environment, which might effect this tracking of a virtual target. We do not account for any objects neither stationary nor moving.

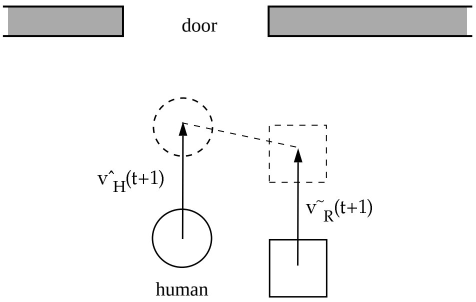
For the wing man's desired velocity $\tilde{v}_W(t+\Delta t)$ we compute then the velocity obstacles for the objects surrounding the wing man. In the ideal circumstances which we assumed for the moment, there is just one velocity obstacle, namely that caused by the accompanied leader. In Figure 3b we see, that the wing man's desired velocity $\tilde{v}_W(t+\Delta t)$ coincides with the apex of the velocity obstacle caused by the accompanied leader but does not lie within VO. Accordingly, $\tilde{v}_W(t+\Delta t)$ is a *reachable avoidance velocity*, i.e. not a colliding velocity, and the wing man can in fact move towards the desired relative position at t. Of course, this is what we expect, but it is still worth mentioning, that in the case of an unobstructed environment the computation of a reachable avoidance velocity does not "overwrite" the desired velocity $\tilde{v}_W(t+\Delta t)$. This will be different in the case of an obstructed environment as we will see in the following section.

A final remark about the wing man's desired $\tilde{v}_W(t+\Delta t)$: As $\tilde{v}_W(t+\Delta t)$ lies outside of VO, it is therefore a reachable avoidance which does not even require a velocity change. So, it is most natural that the wing man maintains this direction and velocity. Now let us ignore for a moment that the wing man is supposed to track a virtual target and thus should follow $\tilde{v}_W(t+\Delta t)$. According to the Velocity Obstacle approach any velocity in the set of reachable avoidance velocities can be chosen in order to avoid a collision with the leader. Of course, the wing man's relative position with respect to the accompanied leader varies depending on which velocity the wing mans selects. In Figure 3b) we see three marked regions in addition to the area representing the velocity obstacle VO, labeled with

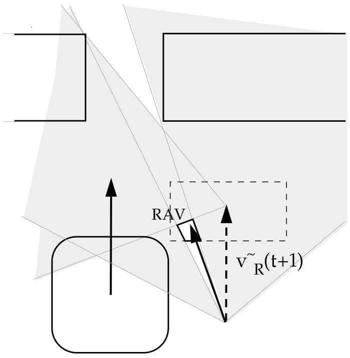
D, F, and B, respectively. If the wing man selects a reachable avoidance velocity, which lies in F, the wing man will speed up, reduce the distance to the leader temporarily and pass to the leader's left in front of the leader. If it selects a reachable avoidance velocity in B, the wing man will fall behind, still approach the leader, but pass it in its rear. If the wing man selects a velocity in D it will steadily increase the distance to and depart from the leader.

2.4 Motion coordination with perturbation — passing through a door

Somewhat more difficult than moving side by side through an unobstructed environment is the situation, when leader and wing man have to pass through a narrow door or a narrow hallway. Apparently the wing man will have to adapt its relative position with respect to the accompanied leader depending and account for the environmental conditions while it still tries to accompany the leader.



a) work space



b) configuration space

Figure 4: Leader and wing man passing through a door

An instance of such a situation is shown in Figure 4a). Leader and wing man approach a door, which is too narrow to allow the wing man accompanying the leader as it would in an unobstructed environment. How does our approach handle this situation?

Like in an unobstructed environment we determine the relative position which the wing man should maintain in order to accompany the leader and compute the desired velocity $\tilde{v}_W(t+\Delta t)$ which is requested for such a behavior. Note, that in the example the virtual target $\tilde{p}_W(t+\Delta t)$ may lie behind the wall or even coincide with the wall.

We then compute the velocity obstacles for all the obstacles in the scene based on the wing man's requested velocity $\tilde{v}_W(t+\Delta t)$ and determine the set of reachable avoidance velocities (RAV). Both the velocity obstacles and the RAV set are shown in Figure 4b). We can see in the figure that the requested velocity $\tilde{v}_W(t+\Delta t)$ (dashed arrow) in this scenario is not in the set. The Velocity Obstacle approach "overwrites" $\tilde{v}_W(t+\Delta t)$ and yields a velocity (bold arrow) which allows to avoid any collisions and minimizes the deviation with respect to $\tilde{v}_W(t+\Delta t)$.

This commanded velocity lets the wing man slow down, reduce the distance, and fall behind the leader. Further iterations of this procedure will slow down the wing man even further until it gets entirely behind the accompanied leader. The wing man will pass the door behind the accompanied leader and then speed up again in order to reach the desired relative position again.

This behavior automatically results from the combination of the Virtual Target Tracking approach with the Velocity Obstacle approach. It does not require any additional mechanisms.

3 Experimental Results

The above function has been extensively and successfully tested in the concourse of the central station of in Ulm, Germany, during regular business hours. The mission was for the robot to accompany a person side by side in a lateral distance of 60 cm through the concourse. The concourse has a size of

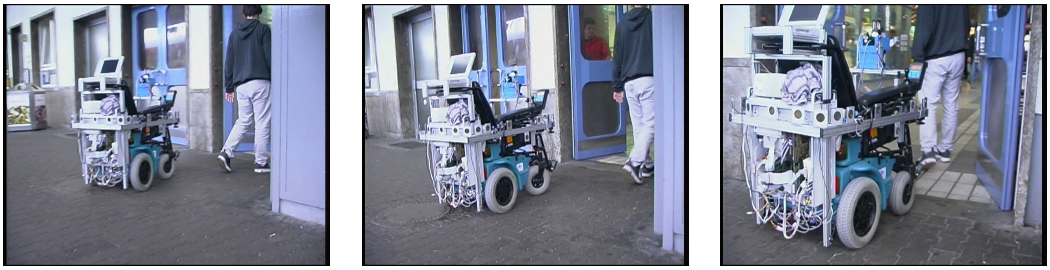


Figure 5: Experiments

about 20×40 m^2, with several rows of seats, an information booth and several ticket machines. The total mission time adds up to 8-10 hours distributed over several days. The distance traveled during that time adds up to around three kilometers. However, due to visibility problems such as occlusion, the robot occasionally lost the person which it had to accompany and then stopped.

In Figure 5 an experiment is shown, where the formation human and robot, move through a door. The first picture shows the robot which is leaving its ideal accompanying position and getting back behind the person. In the second picture the robot has completely taken a following position and passes the door behind the person as shown in the last picture.

4 Conclusion

In this paper we described an approach to moving several objects in formation through a busy, natural environment. Our test application is a robotic wheelchair accompanying a person through the concourse of a railway station moving side by side with the person. During several experiments the robot successfully managed to accompany a person through a populated concourse over a total distance of around three kilometers with a total mission time of 8-10 hours.

Acknowledgement

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