Basic Concepts and Methods for Keeping Autonomous Ground Vehicle Formations

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Abstract

A desirable basic behavior of a group of autonomous vehicles while in motion is to keep a predefined formation. Normally units are trained to move in formation according to an operational status. Past experience determines the formation for given situations. In this paper, we discuss concepts pertinent to the theory and design of autonomous vehicles moving in formation. Specifically: 1) we present the basic idea of controlling the behavior of autonomous vehicles to keep them in prespecified formation, 2) we examine difficulties in keeping the formation caused by path shapes and obstacles in the path of the vehicles and due to the kinematics and dynamics of the individual vehicle, and 3) we discuss concepts relevant to reformation transitions following temporary changes in the formation caused by the terrain properties and the presence of obstacles.

1. Formation Maintenance Principles

1.1 Introduction

When a number of vehicles move in such a way as to maintain a formation they will be referred to as a "moving " unit. The moving unit may include any number of vehicles, but for our purposes we will consider it to be less then 10 vehicles. The main idea of formation is that the vehicles in the unit move together. Each vehicle knows its relative position and the formation structure is suitable for the activity of this unit. Formation type is updated according to type of route, unit hierarchical size, and scenario of the mission. It is necessary for the unit to have a method for maintaining its formation. In units with human drivers, the method is simply "follow the leader". Of course the leader has to adopt a velocity to ensure that all vehicles in the unit are able to stay in formation. Furthermore, each vehicle must be aware of the other vehicles in its neighborhood to avoid collisions and to "stay in line". Let us also assume that the group leader is the point of reference for the formation movement. Suppose that the leader is the only vehicle that knows the general plan and all the other vehicles just have to follow it in a certain structure (Such as line, column, vee formation, etc.). Formation basic parameters should be based on:

- Leading vehicle location, velocity and direction
- Formation type, and distance between vehicles

In the case of autonomous vehicles, following the leader is not accomplished by means of optical equipment but through radio links that ensure communication of the leader's location and velocity (always including the direction of movement). Other vehicle navigation information may be needed in order to keep a very tight formation [1]. As the leader moves along the route, "virtual" formation is attached to its location and to the movement direction [2]. Each vehicle tries to be in its specific position in the "virtual" formation. We propose a basic way to ensure that the entire unit follows the leader in the desired structure. Around each actual vehicle position in the structure, we introduce the concept of a "free space" where the vehicle has to confine its autonomous motion. This ensures collision-free operation areas in the desired unit structure. In Figures 1 and 2 free spaces are shown as circles. The arrow attached to each vehicle designates the desired velocity size and direction.

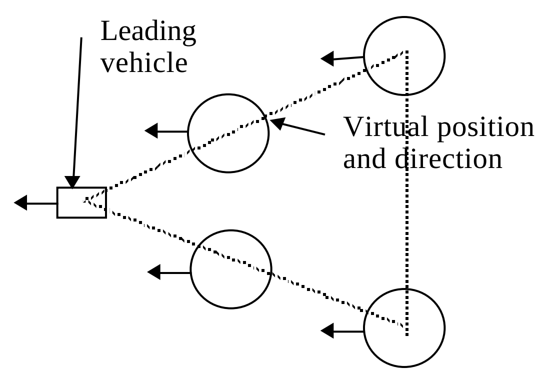

Figure 1: Example of "virtual structure" attached to a leading vehicle

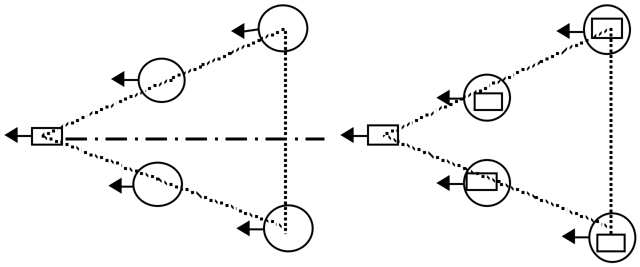

Figure 2: Structure and vehicles keeping formation

1.2 Formation performance measurement

To control the vehicle's formation, we need to define performance measurement parameters. These performance measurements must apply to all terrain situations including obstacle avoidance. See Figure 3, and 4.

Performance involves two types of considerations:

a) Single vehicle performance measurements such as:
   - Distance from the position at the formation “virtual structure” or measures of the vehicle in relation to other vehicles in the formation (like distance or angles).
   - Direction difference between the vehicle direction and the formation direction
   - Velocity difference between each vehicle’s velocity and the leading vehicle velocity.
   - Time to avoid an obstacle and to be back in formation.
   - Performance along the mission: mean values of distance, angle, and velocity difference, and maximum values of distance, direction, and velocity difference.

b) “Group of vehicles” performance measurement such as:

- Vehicles’ Mean/Maximum distance/direction /velocity difference from the “virtual structure”.
- Vehicles’ mean velocity while avoiding obstacles. (There is trade-off between velocity-keeping and formation-keeping while avoiding obstacle.)
- Time that it takes the group to come back to formation after major obstacle avoidance or sharp turning. (The “group” may be defined as the Unit Central Gravity location and direction.)
- Time along the mission that the group was out-of- formation. (Out-of-formation may be defined by threshold of distance/direction/velocity from the “virtual formation”.)
- Formation properties like keeping straight lines very tight.

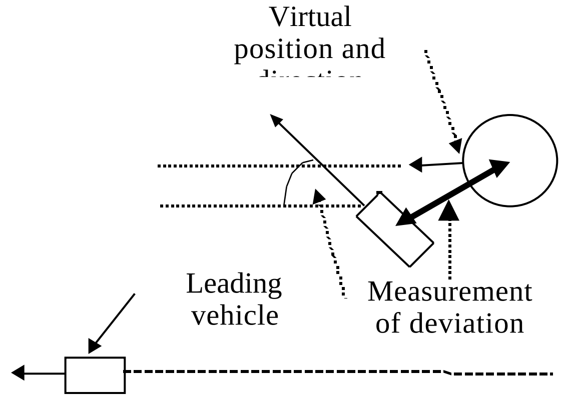

Figure 3: Example of single vehicle performance measurement including differences in position, velocity and direction

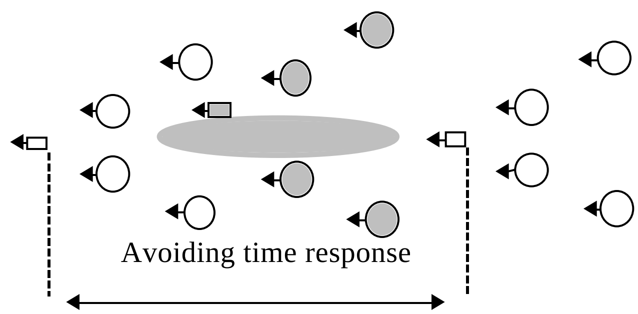

Figure 4: Example of time measurement to avoid obstacle and reform to formation

1.3 Neighborhood relationship in the formation

Neighborhood properties are defined by means of the relationships between the vehicles among themselves, the leader and the terrain through which they are driving. Neighborhood properties may have physical measurable meaning or may be observed phenomena or behavior that relates to a unit or/and its tasks. Neighborhood can be defined mathematically by connectivity properties between points. In this paper, we discuss and illustrate the intuitive notion of neighborhood characteristics in formation maintenance. Neighborhood properties can be bestowed by definition or be received by inheritance through natural hierarchies, Figure 5. The concept of neighborhood is extendable beyond single vehicle performance in the formation as it pertains to global properties of the whole unit. Furthermore, a global neighborhood might be split in subformation behavior applicable for obstacle avoidance, transition to another formation, or to keep the group under control even if the formation is broken.

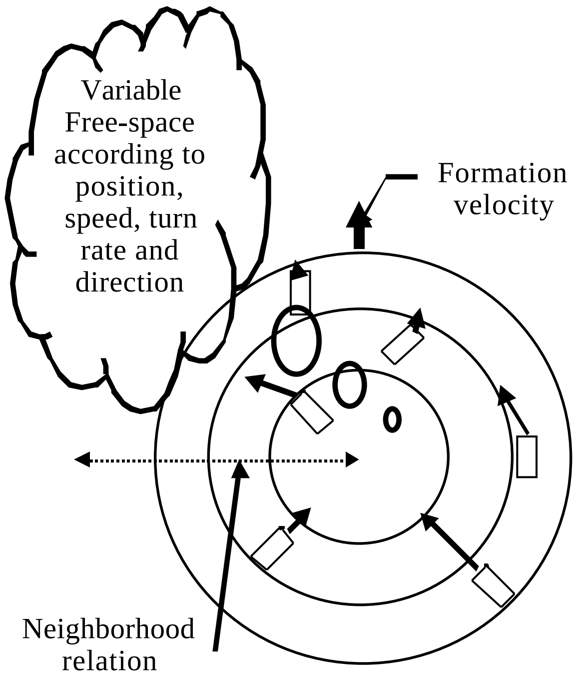

Figure 5: Neighborhood relationship between vehicle and its position in the formation

1.4 Formation disturbance

The formation basic definition constrains the unit's behavior in the presence of natural movement disturbances. Thus, concepts for formation maintenance are needed to cope with basic problems:

- While units are turning due to velocity differences between vehicles in the inner loop and in the outer loop.
- When the leading vehicle turns so sharply that quick relocation of the structure is demanded, including rotation of each of the vehicles.
- When an obstacle in the unit's way causes some vehicles to brake the structure temporarily and then return to the right position relative to the leader.

These issues are illustrated in Figures 6 and 7.

1.5 The role of the leading vehicle and the group leader

The principle duty of the leading vehicle is to plan how the entire group will move in formation and to control the movement of the unit. Usually, it occupies the first place in the formation. For manned vehicles the leading vehicle is the point of reference in "follow the leader rule". Conceptually, vehicles use "point of references" in the formation's "virtual structure" to calculate their "position" in the formation. These calculations may involve parameters from the measurement list above; other parameters may be needed in order to calculate acceptable convenience or robust formation maintenance. Another role of a point-of-reference related to the "structure movement". The planner has to take into account the size of the group and the use points of reference for the origins of the velocity vectors.

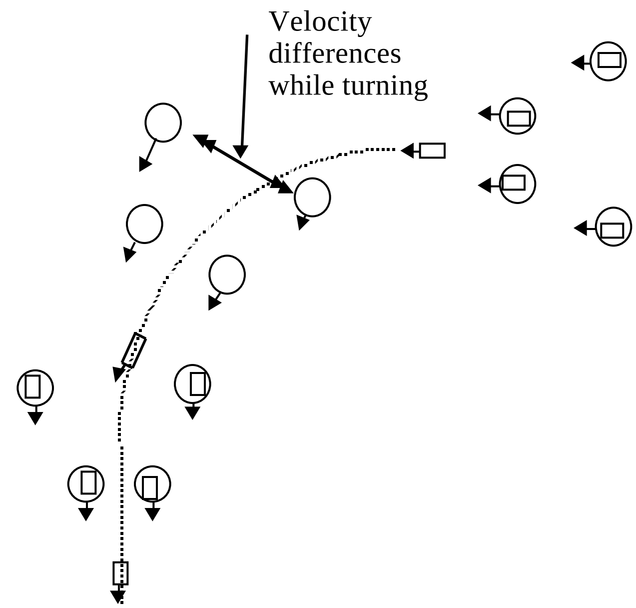

Figure 6: Velocity differences between inner-loop and outer-loop vehicles while turning

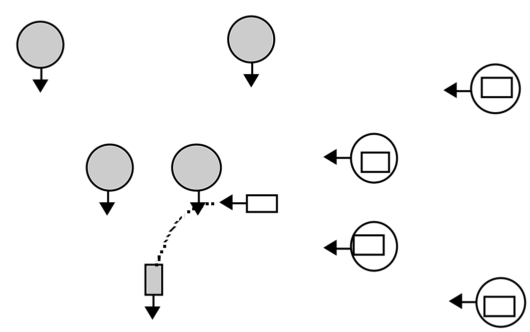

Fig 7: Major relocation and redirection needs after turn of the leading vehicle

The location of the velocity-vector origin in the formation structure is important because it conceptualizes the turning point of the vehicle, Figure 8a and 8b. In reality, the reference point would not be the actual location of the leading vehicle but its position in the virtual structure. The virtual structure is being fitted to current vehicles' position and the direction of the planned movement. This reduces the sensitivity to any changes of the leading vehicle's velocity or direction in the free space. The outcome of this mechanism is that even the leading vehicle follows its position in the structure that is being driven in the movement direction, Figures 9 and 10.

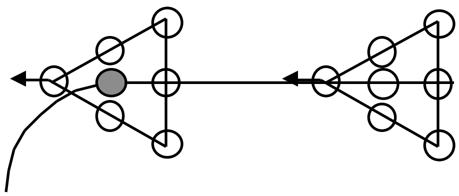

Figure 8a: Formation turning with central gravity as the reference point

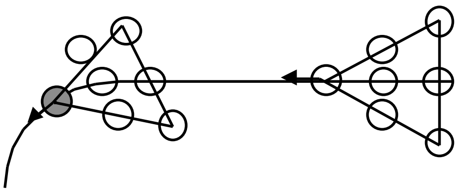

Figure 8b: Formation turning with leading vehicle as the reference point

It is necessary for the leading vehicle to serve as a reference point. Any vehicle in the unit or any point related to the structure may serve as the reference point of the formation-virtual-structure. There are hierarchical organizational requirements such as in the military, which have proved to be highly desirable. Another operational reason is that the lead vehicle can detect unknown obstacles first, react and then update other vehicles.

The selection of the leading vehicle as the unit reference point produces an advantage from communication standpoint. The formation-leading vehicle is the first one to sense and recognize the obstacles that would require changes in the group course and/or formation. However since the leader vehicle has a critical role in the plan, continuous information updating would be required and this choice reduces communication traffic. However, it may cause difficulties concerning the vehicle's behavior in the free space while in obstacle-avoidance-mode. It is necessary to differentiate between local obstacle avoidance of the leading vehicle and those behaviors involving major correction maneuvers of the unit.

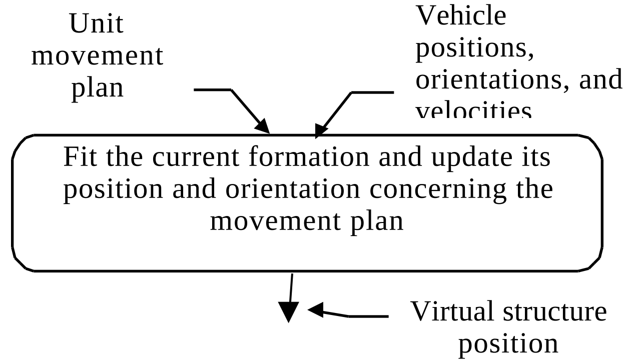

Figure 9: Formation virtual structure handling

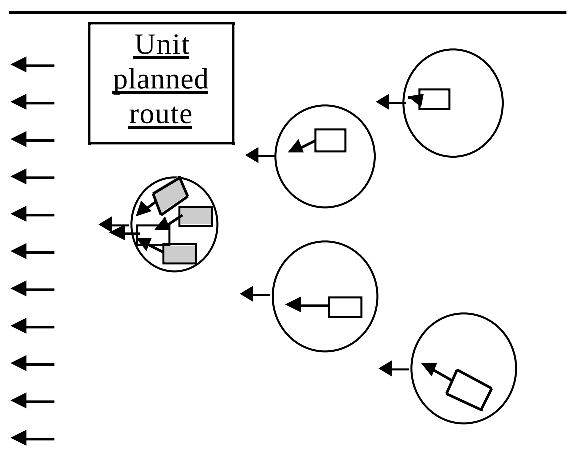

Figure 10: Example to formation virtual-structure fitting including several optional position, orientation and velocity of the leading vehicle

1.6 Maintaining formation while turning (rigid vs. compliant)

Maintaining rigid formation while turning hinders vehicle ability to maneuver. Allowing the formation to be shape compliant on route makes this task easier and make it possible for the formation to return smoothly to its position at the end of the turn. Each vehicle will keep the same distance and the same orientation in relation to the same point on the spine line, as shown in Figure 11.

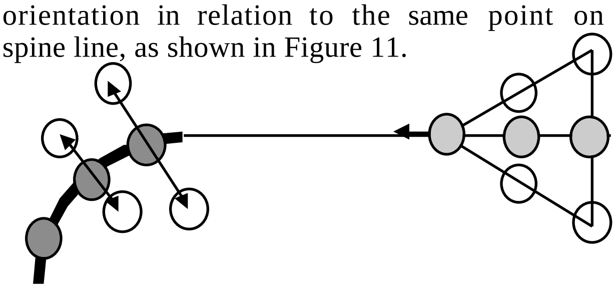

Figure 11: Formation compliance to the route curve

1.7 *Manned vs. unmanned vehicle formations*

Often, manned vehicles formation is defined taking into account the position of a vehicle according to the rank of persons in it (as in the military). The position of particular vehicles may be for safety reasons or, because it enables it to perform specified functions. This means that there is less freedom in switching positions in the formation. In the case of an unmanned vehicle, most of the differences between the vehicles will be based on the installed hardware. If all vehicles have the same capabilities they can switch position and thus recover formation in efficient ways not otherwise possible.

2. Threats to Formation Maintenance

In this section we introduce concepts for dealing with 4 types of threats:

a) Obstacle Avoidance

Clearly there will be occasions that require a vehicle to adjust its path in order to avoid an obstacle. However, there is also a need to avoid collisions between vehicles and to maintain the formation's general structure. One approach is to allow each vehicle to have a bigger "free space" in the "virtual structure". This space will ensure a safety margin to avoid collisions via communications. Alert will be sent to the entire unit if a vehicle is forced to be out of its "free space. In this scenario, knowing the leader position is not enough. For a tight formation the entire group will have to respond to changes in position and direction of vehicles in the formation. This requires continuous communication between all the vehicles. Moreover, the leader becomes less important in the formation maintenance if the focus is on the unit's center-of-gravity movement. Other important issues are:

- The location, velocity and velocity direction of each vehicle.
- The Unit Central-of-Gravity location and direction.
- Formation properties, such as: angles, accuracy of line linearity, etc.
- Avoidance of obstacle to the entire unit (like mountain or roadblock).
- Avoidance of obstacle by single vehicle (like a big rock) or by organized dispersion into subgroups (with leader for each subgroup).
- Formation-keeping based on cooperation between the vehicles.

b) Routes with Sharp Curvatures

Turning a unit while keeping formation involves control of the position, the location and the velocity of each vehicle. The leader vehicle may have to slow down, outer-loop vehicles must increase velocity while inner-loop vehicles must decrease velocity. This requires planning to prevent collision between vehicles. In cases of wide unit (100 m to 500 m or more) a sharp curvature might mean that there will be overlapping between part of the unit while turning as in Figure 12. Thus, planning a route with formation-keeping must take into consideration the size of the unit. A sharp curvature route case may require "position switching". That means that vehicles will switch their position in the "virtual structure" in order to allow turning sharply in the shortest time. The same behavior may be needed to return the formation to original shape after obstacle avoidance.

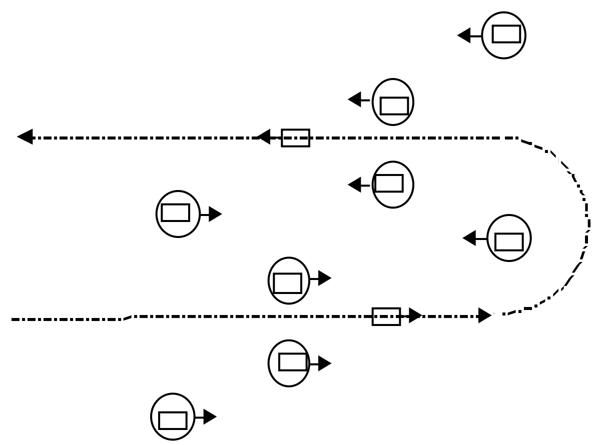

Figure 12: Overlapping of units while turning

c) Vehicles Kinematics and Dynamics

Vehicle time-response to turning and velocity commands (dynamic) and vehicle turn rate (or turning radius) according to the velocity (kinematic) influence the close loop control of the relative positions of the vehicles. Kinematics is the main influence when the vehicles have to do a large correction in their position and direction (like in sharp turns). As all planned vehicles' trajectories would not have identical length and velocity parameters, in some scenarios it may necessary for the leader to stop and wait. In other situations, kinematics can cause a collision between the vehicles. Kinematic consideration may be solved by "position switching". In Figures 13 and 14 we show scenarios where kinematic constraints demand trajectory and velocity planning in order to complete a turn.

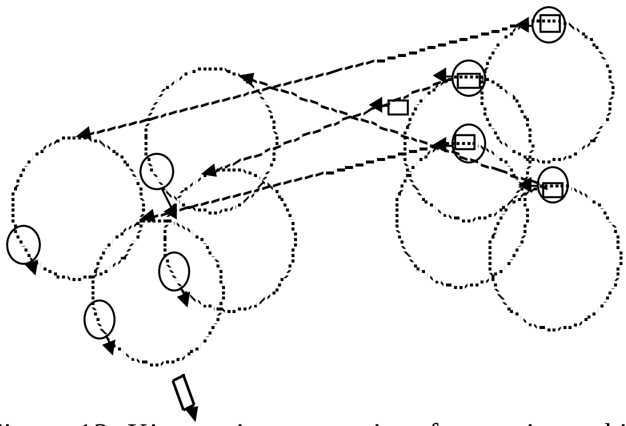

Figure 13: Kinematics constraints for turning while keeping formation

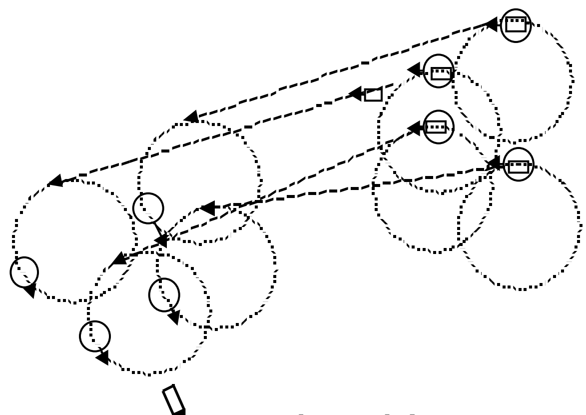

Figure 14: Position switching while turning to allow routes with similar length

d) Temporary Formation Disturbance

Such disturbances may be treated either by: a) overcoming the disturbance in the vehicle level while maintenance acceptable formation deviations or b) by changing the type of formation temporarily. However, there are situations where formation change is mandatory, as in case of crossing a narrow bridge. The unit must switch temporarily to a column formation, Figure 15, and then return to its original formation after crossing.

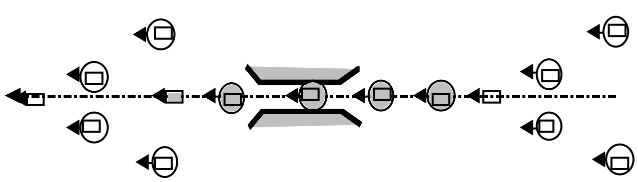

Figure 15: Crossing bridge while keeping formation

In either case, initiation of a recovery from temporary acceptable formation involves complex processes beyond the scope of this paper. However, our preliminary results in this area suggest that the concepts and methods we presented here provide a good starting point for developing a promising theory and design methodology.

3. Concluding Remarks

We have introduced fundamentals of a conceptual framework for formation keeping. We formulated it specifically for studying problems encountered in the design and maintenance of well-structured movement of group of autonomous vehicles. The notions of: “moving unit”, “virtual structure”, and “vehicle neighborhoods” provide the foundations for this framework. While they can be defined as strictly topological ideas on the basis of a rigorous mathematical formalism, they were described here on intuitive basis. We focused on: 1) illustrating their effectiveness in engineering a conceptualization of selected, basic, formation-keeping problems encountered by small groups of autonomous vehicles, and 2) their promise to suggest acceptable problem solution by modern computational and/or simulation techniques. The applications of these concepts and methods to specific practical problems similar to those we discuss here appear to be straightforward.

4. References

[1] S. Sheikholeslam and C. A. Desoer "Control of Interconnected Nonlinear Dynamic Systems: The Platoon Problem", IEEE Trans. on Automatic Control, pp 806-810, (1992).

[2] M. Anthony Lewis and Kar-Han Tan, "High Precision Formation Control of Mobile Robots Using Virtual Structures", Autonomous Robots 4, pp 387-403, (1997).