ON-GROUND PATH PLANNING EXPERIMENTS FOR MULTIPLE SATELLITES

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Abstract: *This paper presents a path-planning and collision avoidance method for satellite formations and swarms and its validation in simulation and in a testbed on ground. The path-planning technique uses the definition of several behavior functions like Gather, Avoid and Dock, which form a virtual potential from which desired velocities are computed. A controller is used to achieve these velocities by commanding the onboard thrusters. This method has been validated in simulation and on the Test Environment for Applications of Multiple Spacecraft (TEAMS), a test facility for satellite formations and swarms based on air cushion vehicles. The vehicles are floating on two granite tables with a total experiment area of 5m x 4m. Each vehicle has a thruster system and its own onboard computer on which the presented path-planning algorithm is running together with a Kalman-Filter for state estimation, an attitude control and a thruster actuation algorithm. Experiments performed in simulation and on the testbed include formation acquisition and reconfiguration as well as collision avoidance. Experiment results are presented and show the performance and the robustness of the implemented guidance algorithm, as well as the test readiness of the TEAMS facility.*

Keywords: *Testbed, satellite swarms, virtual potential, collision avoidance, formation flying.*

1. Introduction

These days the size of satellites is limited due to the available shipping volume of modern launch vehicles. However, larger and larger structures are needed to improve Earth observation capabilities and the resolution of telescopes. Satellite formation flying with two or more satellites can be used to overcome this restriction. This involves coordinated flight between two or more satellites, in which new challenges arise. One of these challenges is the development of new guidance, navigation and control algorithms for formation acquisition, reconfiguration and collision avoidance. Especially for a larger number of satellites, these algorithms must be performed autonomously with only a small interaction from the operator.

To test these algorithms in a realistic environment the Test Environment for Applications of Multiple Spacecraft (TEAMS) test facility has been developed and built up at the Institute of Space Systems in Bremen, Germany. The testbed is a laboratory for simulating the force and torque free dynamics of several satellites on ground using air cushion vehicles floating on two big granite tables. It can be used to simulate precise formation flying, as in astronomical missions, and attitude control using 2 vehicles with a rotatable upper platform. 4 smaller vehicles are also available and can be used to simulate swarm behavior, formation acquisition, reorientation and reconfiguration as well as path-planning algorithms. The facility is also useful for testing sensors for relative attitude and position as well as spacecraft behavior during berthing and docking maneuvers (contact dynamics).

This paper presents the implementation of an autonomous and distributed path planning algorithm for multiple satellite applications in simulation as well as on the TEAMS testbed. The algorithm is based on the virtual potential method. This gives the possibility to include different generic behaviors like gathering, docking and avoiding, without the need for precalculation of desired trajectories. From the potentials desired velocities are computed onboard, which are controlled using a control algorithm.

The path-planning algorithm has not only been implemented in simulation to show its functionality but is also used to guide and control the vehicles of the TEAMS testbed. The guidance algorithm is running in real-time on the on-board computers together with a Kalman-Filter for state estimation, attitude control and thruster actuation algorithms. Several experiments have been performed in simulation and on the testbed. They include formation acquisition and reconfiguration, as well as collision avoidance. The results of the experiments will show the performance and the robustness of the implemented guidance algorithm, as well as the capability of the TEAMS facility to test such types of algorithms.

2. Path-planning and control

The path-planning approach used in this paper has been proposed by Izzo and Pettazzi [1]. It is based on the definition of a virtual potential field from which desired velocities $\underline{v}_d$ can be derived. These desired velocities are a sum of different weighted contributions named "behaviors". To track the desired velocity different control methods can be used.

2.1. Definition of the kinematical field

Given N spacecraft (agents) with their position $\underline{x}_i$ in the local horizontal local vertical (LHLV) reference frame and the same number of target points at position $\underline{\xi}_j$. To steer these agents to their target positions 3 different behaviors are introduced.

The *Gather* behavior makes the agents move in the direction of the targets:

$$\underline{v}_i^{Gather} = \sum_j c_i \left(\underline{\xi}_j - \underline{x}_i \right) \tag{1}$$

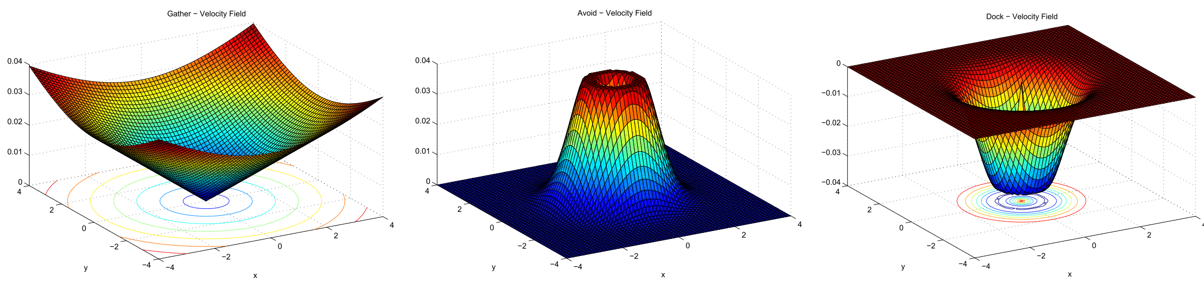
with positive constants c_i defining the intensity of the attraction. The desired velocity is proportional to the distance and as such globally effective (see Fig. 1(a)).

The *Avoid* behavior defines an interaction between different spacecraft. In case that these spacecraft are in proximity to each other a repulsive component is added to the kinematical field:

$$\underline{v}_i^{Avoid} = \sum_j -b_i \exp\left(-\frac{\left\| \underline{x}_j - \underline{x}_i \right\|^2}{k_{a,i}} \right) \left(\underline{x}_j - \underline{x}_i \right) \tag{2}$$

with the positive constants b_i, which defines the intensity, and $k_{a,i}$, which defines the sphere of influence (see Fig. 1(b)).

Finally, the *Dock* behavior defines local attractors towards the target points (see Fig. 1(c)). This behavior has only a nonnegligible value in the vicinity of the target points. Again, a constant d_i is



(a) Gather behavior (b) Avoid behavior (c) Dock behavior

Figure 1. Agent behaviors

defined for the intensity and a constant $k_{d,i}$ for the sphere of influence:

$$\underline{v}_i^{Dock} = \sum_j d_i \exp\left(-\frac{\left\|\underline{\xi}_j - \underline{x}_i\right\|^2}{k_{d,i}}\right)\left(\underline{\xi}_j - \underline{x}_i\right). \tag{3}$$

The total desired velocity for each spacecraft $\underline{v}_i$ is the sum of these three components:

$$\underline{v}_i = \underline{v}_i^{Gather} + \underline{v}_i^{Avoid} + \underline{v}_i^{Dock}. \tag{4}$$

Assuming a symmetric formation configuration, the parameter vector $\underline{\lambda}_i = \left[b_i, c_i, d_i, k_{a,i}, k_{d,i}\right]$ will be the same for each spacecraft. The parameter vector $\underline{\lambda}$ has to be chosen such that the final configuration is an equilibrium point (*Equilibrium Shaping*). That means that the desired velocity must be zero when the agents have reached their final position:

$$\underline{v}_i\left(\underline{x}, \underline{\xi}, \underline{\lambda}\right)\Big|_{\underline{x}=\underline{\xi}} = 0. \tag{5}$$

This results in a system of equations which can be solved for one parameter if the others are given.

2.2. Utilization of the gravitational field

The method described in the previous section makes the spacecraft reaching their targets on trajectories which are not fuel-optimal. For large distances only the Gather behavior has a nonnegligible influence on the trajectory which is the direct way to the target. To get a more optimal solution this behavior has to be exchanged.

Starting from the Hill equation [2]:

$$\begin{aligned} \ddot{x} - 2\omega\dot{y} - 3\omega^2 x &= 0 \\ \ddot{y} + 2\omega\dot{x} &= 0 \\ \ddot{z} + \omega^2 z &= 0 \end{aligned} \tag{6}$$

with the position $\underline{x} = [x, y, z]$ given in a LHLV coordinate frame rotating with an angular rate ω on a circular orbit one gets the well-known closed-form analytical solution [2]:

$$\begin{bmatrix} \underline{x} \\ \dot{\underline{x}} \end{bmatrix} = \begin{bmatrix} \underline{A}(t) & \underline{B}(t) \\ \underline{C}(t) & \underline{D}(t) \end{bmatrix} \begin{bmatrix} \underline{x}_0 \\ \dot{\underline{x}}_0 \end{bmatrix}. \tag{7}$$

So a spacecraft being at position $\underline{x}_i = \underline{x}_0$ and aiming for the center of a target configuration $\frac{1}{N}\sum_j \underline{\xi}_j$ within the time t_d should have the desired velocity

$$\underline{v}_i^{Gather} = \underline{B}^{-1}\frac{1}{N}\sum_j \underline{\xi}_j - \underline{B}^{-1}\underline{A}\,\underline{x}_i \tag{8}$$

with $\underline{A} = \underline{A}(t_d - t)$ and $\underline{B} = \underline{B}(t_d - t)$. This solution can be used to define a new Gather behavior, which is added to the Avoid and Dock behavior. For $t \to t_d$ the new Gather behavior gets singular. To overcome this problem a sphere with the radius R_{ge} around the target center is defined. Outside this sphere the new Gather behavior will be used. A spacecraft entering this sphere switches back to the normal Gather behavior (Eq. 1).

2.3. Control methods

The kinematical field computes desired velocities. To reach these velocities each vehicle needs a controller to produce the needed thrust. In [1] three different control methods have been proposed: "Q-Guidance", "Sliding-Mode Control" and "Artificial Potential". These three methods have been compared to each other and the "Artificial Potential" approach has been chosen for further simulations and experiments on the testbed [3].

The feedback control law can be obtained from the virtual potential function given by

$$V = \frac{1}{2}\sum_i \underline{v}_i\underline{v}_i + \sum_i\sum_{j\neq i}\phi_A^{ij}\left(\underline{x}_i - \underline{x}_j\right) + \sum_i\sum_j \phi_G^{ij}\left(\underline{x}_i - \underline{\xi}_j\right) + \sum_i\sum_j \phi_D^{ij}\left(\underline{x}_i - \underline{\xi}_j\right) \tag{9}$$

with

$$\frac{\partial \phi_A^{ij}}{\partial \underline{x}_i} = -\underline{v}_i^{Avoid} \qquad \frac{\partial \phi_G^{ij}}{\partial \underline{x}_i} = -\underline{v}_i^{Gather} \qquad \frac{\partial \phi_D^{ij}}{\partial \underline{x}_i} = -\underline{v}_i^{Dock}. \tag{10}$$

This function has equilibrium points for each combination of agents at the target points $\underline{\xi}_i$. According to Lyapunov's theorem the system will reach its equilibrium point if

$$\dot{V} = \sum_i \left(\frac{\partial V}{\partial \underline{x}_i}\dot{\underline{x}}_i + \frac{\partial V}{\partial \underline{v}_i}\dot{\underline{v}}_i\right) = \sum_i \left(\dot{\underline{v}}_i - \underline{v}_{d_i}\right)\underline{v}_i < 0. \tag{11}$$

Using the feedback law

$$\underline{u}_i = \underline{v}_{d_i} - \kappa_i\underline{v}_i - \underline{a}_{in_i} \tag{12}$$

and the dynamics given in Eq. 6 the time derivative of the potential function is

$$\dot{V} = \sum_i \underline{v}_i\left(-\kappa_i\underline{v}_i + \underline{a}_{dis}\right) \tag{13}$$

with the acceleration due to non-modeled disturbance forces $\underline{a}_{dis}$. This can be made negative as long as the lower bound $\kappa_i > \frac{\|\underline{a}_{dis}\|}{\|\underline{v}_i\|}$ is applied.

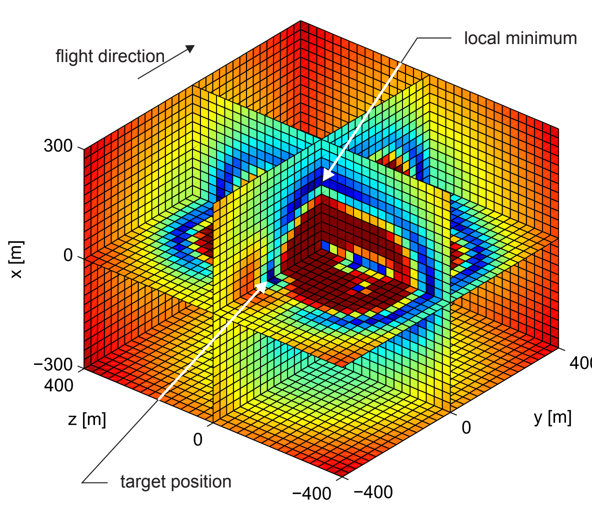
3. Simulation results

To test and validate the developed path-planning algorithms an orbit simulation has been built up using the High Performance Satellite Dynamics Simulator HPS [4]. The simulation consists of the spacecraft dynamics, a simple gravitational model of the Earth, atmospheric drag and a thruster saturation.

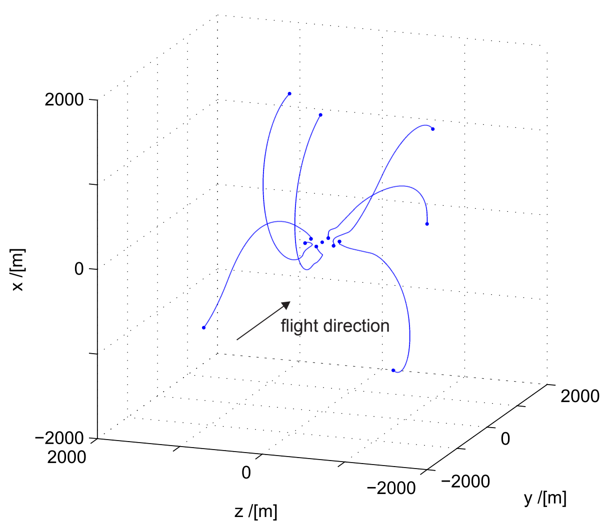
The scenario that has been used in the simulation consists of six satellites placed in the shape of a hexagon around one central satellite. The satellites are flying in a low Earth orbit (LEO) at 650 km altitude. The distance of each satellite to the central satellite is 200 m. A possible mission where a similar configuration is used is the DARWIN mission [5].

The maximum acceleration which can be produced by the thrusters of one satellite is $a_{th,max} = 0.005\,\mathrm{m/s}^2$. The parameters that define the sphere of influence for the *Avoid* and *Dock* behavior are set to $k_a = k_d = (100\,\mathrm{m})^2$. To decelerate a spacecraft within 100 m using the available thrusters a maximum velocity of $v_{max} = 1\,\mathrm{m\,/s}$ has been chosen. This can be achieved by setting the parameters $b = 0.025\,\mathrm{s}^{-1}$ and $d = 0.005\,\mathrm{s}^{-1}$. The last parameter is computed using the *Equilibrium Shaping* method to $c = 1.0471\,\mathrm{s}^{-1}$. Outside a sphere of $R_{ge} = 800\,\mathrm{m}$ the *Gather* behavior from Eq. 8 is used which utilizes the gravitational field. Inside the sphere the *Gather* behavior from Eq. 1 is used.

At the begin of the simulation the satellites are distributed randomly on a sphere around the central satellite with a radius of 2000 m. A successful formation acquisition can be seen in Fig. 2(b).



(a) Kinematical field

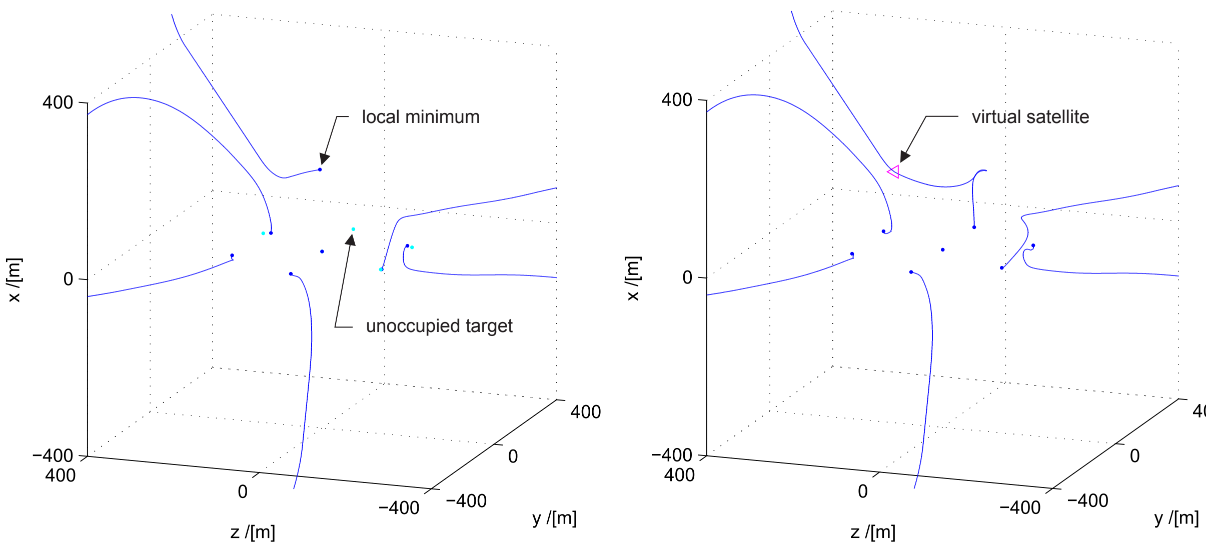


(b) Agent trajectories

Figure 2. Formation acquisition in LEO

One disadvantage of the used method for path-planning can be seen in this example. Beside the target points $\underline{\xi}$ other unwanted minimums can exist in the kinematical field (Fig. 2(a)). Depending on the initial configuration satellites can end up in one of those minimums (Fig. 3(a)). Different approaches exist to overcome this problem.

One approach is the implementation of virtual satellites. If the desired velocity of one agent drops below a predefined value v_{min} the algorithm checks if this agent is in the sphere of influence of one target. That means that the distance to a target is below R_{min}. If not, a virtual satellite is implemented at the position of the agent. The *Avoid* behavior of the virtual satellite guaranties that the agent does not rest in the undesired local minimum of the virtual potential. If the agent reaches the sphere of influence R_{min} of one target afterwards, the virtual satellite is deactivated. Otherwise the formation would not reach the desired equilibrium state. One example trajectory can be seen in Fig. 3(b). The agent successfully avoids the undesired minimum shown in Fig. 2(a) and reaches the desired equilibrium state.



(a) Failed acquisition (b) Successful acquisition with virtual satellite

Figure 3. Formation acquisition in LEO with local minimum

Another approach is the increase of the desired velocity outside the spheres of influence of the different target points such that the velocity is at least the minimum velocity v_{min}.

4. Validation on testbed

4.1. The TEAMS facility

For the on-ground validation of the path-planning and control algorithms the TEAMS (Test Environment for Applications of Multiple Spacecraft) facility at the Institute of Space Systems of the German Aerospace Center in Bremen has been used.

TEAMS is a laboratory to emulate the force and torque free dynamics of satellites on ground. It consists of two granite tables with a total experiment area of 5 m by 4 m (see Fig. 4). The surface of each table has been manufactured with an accuracy of 3 µm. In addition the tables have been leveled with an accuracy of less than 20 µm from one edge to the other and with an accuracy of less than 10 µm from one table to the other.

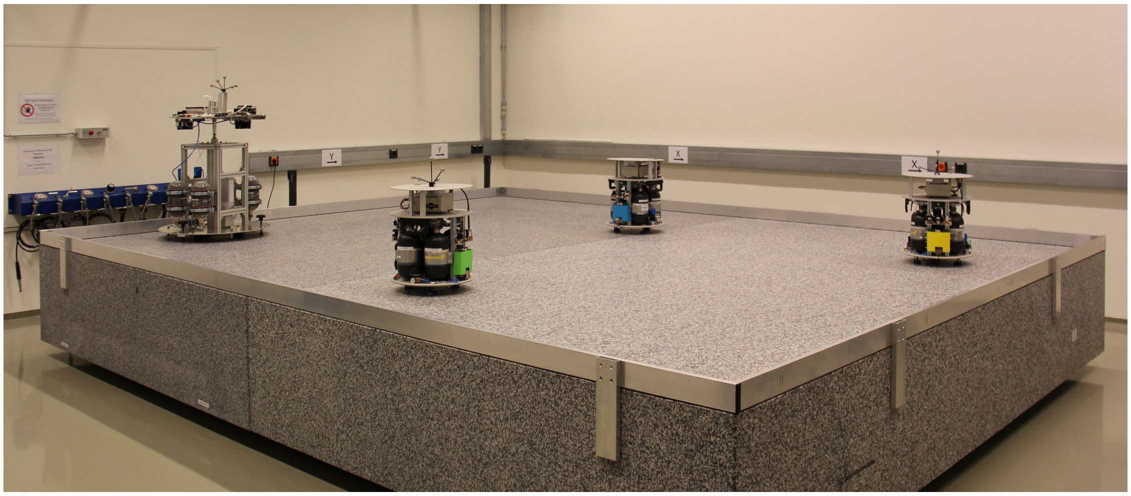


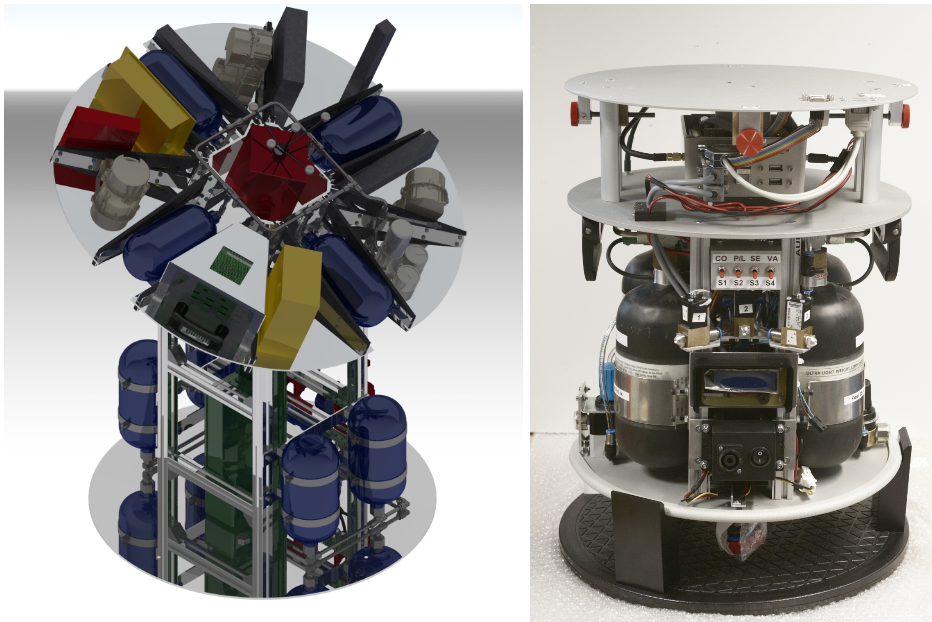
Figure 4. TEAMS laboratory

Spacecraft are represented by air cushion vehicles. Two types of air cushion vehicles are used: The 2 bigger ones called TEAMS_5D have an actuated linear stage to simulate movement in the *z*-axis and will have a rotatable upper platform to simulate attitude dynamics ("Attitude Platform"). These vehicles can emulate 5 degrees of freedom (see Fig. 5(a)). The 4 smaller vehicles are called TEAMS_3D and are able to emulate 3 degrees of freedom (Fig. 5(b)). These are used mainly for swarm simulations.

Beneath each vehicle three air cushion pads generate a small air film on which the vehicles can float frictionless. The air for the air bearings as well as for the thrusters is stored in several 300 bar air tanks. Pressure regulators regulate the air pressure down to 6–8 bar. On the TEAMS_5D vehicles a spherical air bearing supports the rotatable upper platform.

A *DTrack* infrared tracking system is used as main sensor for position and attitude. Several reflective balls are mounted on each vehicle and are tracked by 6 infrared cameras. By combining the images of these cameras the tracking system can compute position and attitude of each vehicle. As the configuration of the reflective balls is different for each vehicle the system is able to distinguish between the agents. The position and attitude of each vehicle is distributed over the local wireless network and can be used by each onboard computer. In addition the TEAMS_5D vehicles will also use an inertial measurement unit with three fiber optic gyros and three MEMS accelerometers.

To control position and attitude the vehicles are equipped with proportional coldgas thrusters supported by 6 bar pressurized air. The TEAMS_5D thrusters can produce a maximum thrust of 65 mN while the maximum thrust of the TEAMS_3D thrusters is 47 mN. Depending on thruster configuration and vehicle mass the thruster system can produce a acceleration of 2.8 mm/s^2 (TEAMS_5D, current configuration) and 5.5 mm/s^2 (TEAMS_3D). In addition the attitude platform of the TEAMS_5D vehicles will be equipped with 3 reaction wheels with a maximum commandable torque of 0.015 Nm and a maximum angular momentum of 0.36 Nms. As these wheels are only for attitude control they are not used in the experiments described in this paper.



(a) TEAMS_5D (b) TEAMS_3D

Figure 5. TEAMS air cushion vehicles

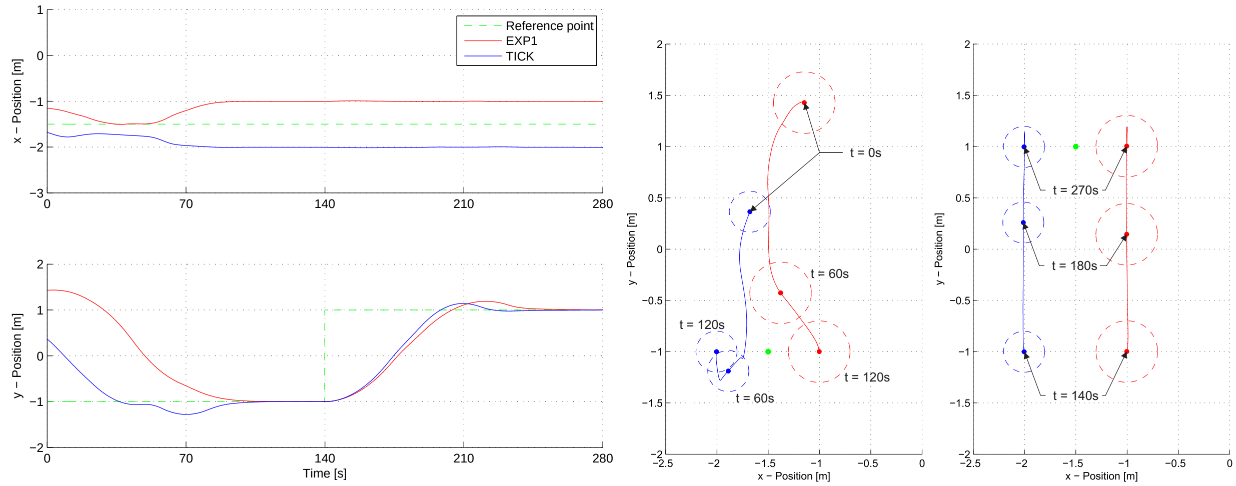
As onboard computer an embedded x86 Atom Z530 on a PC104 stack is used running the *QNX* RTOS. Via a WLAN connection software and parameters can be uploaded and realtime data can be downloaded, displayed or saved. Control algorithms are developed using *Matlab/Simulink* together with *Real-Time Workshop* (RTW) for automatic generation of C-code.

Beside the described control and path-planning algorithms a Kalman-Filter for state estimation, a thruster actuation (TA) algorithm as well as algorithms for attitude control are running on the onboard computer. The Kalman-Filter is a static gain filter for estimation of velocities, attitude rate, constant disturbing acceleration and constant disturbing angular acceleration. The TA algorithm is needed to compute the needed thrust of each thruster given the thruster configuration and the commanded forces and torques. Attitude control around the z-axis is implemented as a LQR with static disturbance rejection using the outputs of the Kalman-Filter (see [6]).

4.2. Results

The experiments presented in the following section has been made using the currently available TEAMS_5D vehicle called “Exp1” and one TEAMS_3D vehicle called “Tick”. Similar to the parameter choice in section 3. the size of the sphere of influence for the *Avoid* and *Dock* behavior have been chosen to $k_a = k_d = (0.5\,\mathrm{m})^2$. The maximum velocity $v_{max} = 0.07\,\mathrm{m\,/s}$ has been set such that the vehicles can decelerate within one meter. This results in the choice of the parameters $b = 1.2\,\mathrm{s}^{-1}$ and $d = 0.1\,\mathrm{s}^{-1}$. Using the *Equilibrium Shaping* method the last parameter can be computed to $c = 0.0102\,\mathrm{s}^{-1}$.

The experiment presented in this section includes a formation acquisition as well as a formation



(a) Formation acquisition and repositioning (b) Formation acquisition (c) Formation repositioning

Figure 6. Formation acquisition and repositioning for a fixed target

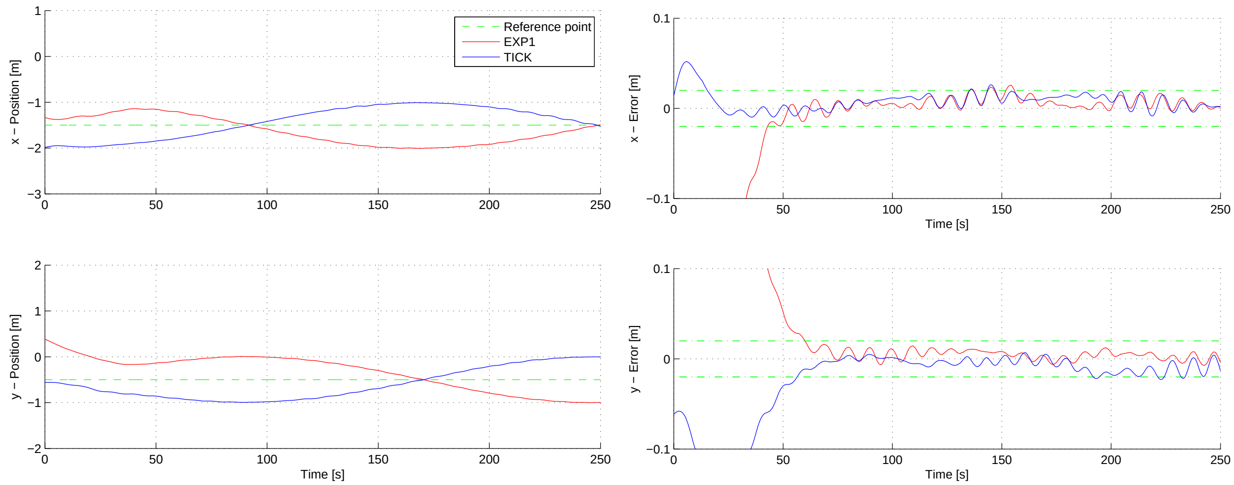
reconfiguration. At the beginning of the experiment the vehicles are placed randomly on the table. The target points are defined to $\underline{\xi}_1 = [-1\,\mathrm{m}, -1\,\mathrm{m}]$ and $\underline{\xi}_2 = [-2\,\mathrm{m}, -1\,\mathrm{m}]$. The results are shown in Fig. 6(a) and Fig. 6(b).

At the beginning both vehicles orient themselves in the direction of the formation center. At this point the kinematical field is mainly influenced by the *Gather* behavior. The smaller "Tick" vehicle is the first to arrive at the reference y-value and waits near its final position for the arrival of the "Exp1" vehicle. The bigger "Exp1" vehicle than pushes the "Tick" vehicle into its final target position. The acquisition time for the total formation is about 100 s and the residual control error is below 5 mm.

At $t = 140\,\mathrm{s}$ the formation has been reconfigured and new reference points were given. Both vehicle drift to their new target points in an almost parallel way. The acquisition time for this maneuver is about 110 s.

A second experiment demonstrates the acquisition of a rotating formation. The parameters for the kinematical field are the same as in the previous experiment but the target points are rotating on opposite positions around the reference point with $\omega = 0.03\,\mathrm{s}^{-1}$ on a circle with radius $r = 0.5\,\mathrm{m}$. At the begin of the experiment the vehicles have been placed randomly on the table. The results are shown in Fig. 7.

The vehicles reach their target points successfully after 61 s. Looking in the details of the control error one can see an oscillation of both vehicles in x as well as in y direction. The reason for this is that the *Avoid* behavior has a strong influence even when both vehicles have reached their target position. The nonlinear feedback from position to desired velocity (Eq. 2) leads to a limit cycle of a nonlinear system of second order. Lowering the strength of the kinematical field would also lower the amplitude of the limit cycle but would also increase acquisition time. Another possible solution for this problem is to reduce the sphere of influence of the *Avoid* behavior which will lower



(a) Vehicle position

(b) Control error

Figure 7. Acquisition of a rotating formation

the influence of the *Avoid* behavior on a neighbor vehicle when in final configuration. Again this would lower the amplitude of the limit cycle. The best solution is to adapt the *Avoid* behavior such that there is no influence on other vehicles when outside the sphere of influence.

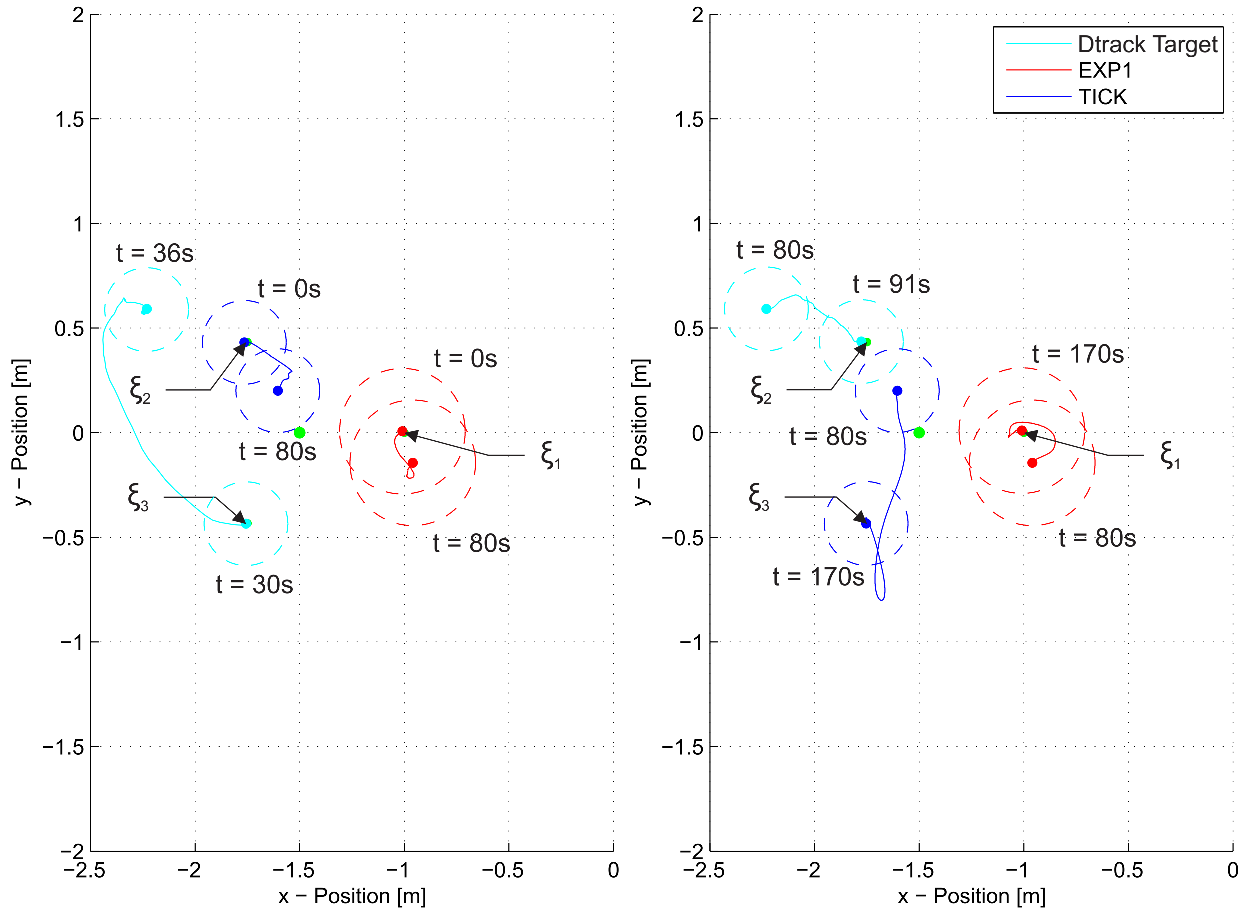
The last experiment shows the collision avoidance capabilities of the presented path-planning algorithm. For that a formation consisting of three vehicles forming an equilateral triangle is used. Again, the vehicles “Tick” and “Exp1” are used. The third agent is not a real vehicle but a target of the tracking system, which can be moved manually. But for the other vehicles it is seen as a third agent. As a different formation configuration is used, the parameters for the kinematical field have to be recalculated. They are set to $k_a = k_d = 0.2\,\mathrm{m}^2$, $b = 0.7\,\mathrm{s}^{-1}$, $d = 0.1\,\mathrm{s}^{-1}$ and $c = 0.0141\,\mathrm{s}^{-1}$.

Between $t = 0\,\mathrm{s}$ and $t = 30\,\mathrm{s}$ the formation is in equilibrium state in its final configuration (see Fig. 8(a)). At $t = 30\,\mathrm{s}$ the target of the tracking system is moved according to the trajectory in Fig. 8(a). This simulates an abnormal behavior of one satellite. The “Tick” as well as the “Exp1” vehicle start to move away to avoid an collision with the third agent. As the third agent is not at a target point, both other agents don’t move to a target point neither.

Putting the tracking target in the target point $\underline{\xi}_2$ at $t = 91\,\mathrm{s}$ the two vehicles start to rebuild the desired formation automatically and move to the other target points $\underline{\xi}_1$ and $\underline{\xi}_3$.

5. Conclusions

In this paper we presented the implementation of an autonomous and distributed path-planning method for satellite formations and swarms. The method is based on the definition of a virtual kinematical field from generic behaviors like *Gather*, *Avoid* and *Dock*. In addition a control algorithm is needed to make each satellite follow the defined kinematical field autonomously. This gives us the possibility to do formation acquisition, reconfiguration and reorientation while avoiding collision with other satellites. The method has been implemented in simulation for a formation



(a) Collision avoidance during abnormal vehicle behavior

(b) Autonomous reconfiguration

Figure 8. Collision avoidance and autonomous reconfiguration

of 6 satellites and has been tested on an air-cushion vehicle based testbed. Formation acquisition and reconfiguration have been shown in these environments as well as the capability of the method to do collision avoidance in case of an abnormal behavior of one satellite. Some disadvantages of the implemented method have identified during the experiments. This includes the problem of unintended local minimums of the kinematical field as well as oscillating limit cycles near equilibrium points. For both problems possible solutions have been presented.

The path-planning and control algorithms have been implemented on the TEAMS facility. The capability of the easy implementation of guidance and control algorithms for satellite swarms and formations have been demonstrated with two working vehicles. Three additional air-cushion vehicles will be ready in the near future. Further path-planning experiments with up to 5 vehicles are already planned with improved algorithms.

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