Info Bee at UNICARagil: Support from Above for Automated Driving

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Content

Summary

For autonomous driving, a key requirement is the correct perception of the vehicle's environment. In order to provide additional data on demand, unmanned tiltwing aircraft are used in the research project UNICAR*agil*. By providing a unique point of view, the Info Bee can contribute valuable information in critical situations. This paper presents the Info Bee and provides a solution to path planning challenges arising from street inspection flights at high speed.

1 Introduction

In the research project UNICAR*agil*, a modular framework for autonomous fully-electric road vehicles is developed [1]. The modularity of the framework allows to reuse many modules across different vehicles. This is demonstrated inside the project by building four different vehicle types: autoELF is intended as privately owned family car while autoTAXI allows for personal transport on a per-route payment basis. In contrast to these two small-sized cars, two bigger types are used for package delivery (autoCARGO) as well as local public transport for up to eight persons (autoSHUTTLE).

Despite their different sizes and use cases, all four vehicle types share many modules which therefore only have to be developed once.

One central research domain within UNICAR*agil* covers automation of the vehicles in order to enable driverless operation. Within this project, the environment model generated onboard a vehicle based on its sensor data is augmented by data received from a cloud-based service that consolidates information transmitted by all vehicles. Unmanned tiltwing aircraft, called *Info Bees*, are used to gather additional data using the unique perspective from above.

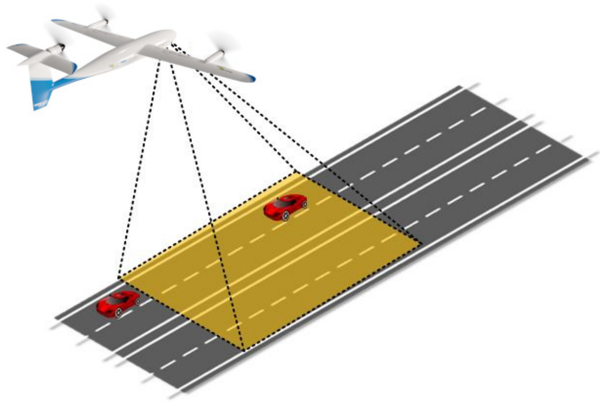

Fig. 1 Info Bee flying above a street and collecting traffic information.

The remainder of the paper is structured as follows:

In the next section, a quick overview of the Collective Environment Model cloud service is given and how an airborne sensor can contribute. Next, the aircraft is presented together with the changes to hardware and software necessary to employ it for the specified use cases. Then, a special approach to path planning is presented to allow high speeds even in the presence of high street curvature. Finally, conclusions and outlook are given.

2 Motivation

A key aspect to autonomous driving is the correct perception of the vehicle's environment. In the UNICAR*agil* project, a Collective Environment Model (CEM) is provided as a cloud-based service [2]. The environment model gathered by a vehicle is transferred to the CEM where it is merged with data reported by other vehicles. In return, the CEM provides every vehicle with consolidated data about its environment, thereby making the vehicle aware even of traffic participants occluded from its view.

This increased awareness offers benefit for example when a car is parked on the street immediately after a narrow turn. Due to occlusion by buildings, it will be invisible to the sensors of a driving vehicle until this vehicle arrives at the turn. As a result, strong deceleration might be necessary resulting in discomfort of the passengers. This situation can be avoided if the cloud informs the vehicle about the upcoming parked car in advance by using data reported by other vehicles that passed that spot earlier.

Environment information shared by the cloud can also improve driving efficiency during the approach of an intersection. Normally, vehicles decelerate when approaching an intersection in order to be able to give way to possible crossing traffic participants. An intersection can only be traversed as soon as the ego vehicle is confident of the absence of potential collision threads, i.e. when the crossing streets are visible. However, if the CEM receives up-to-date information from other vehicles moving on the crossing streets that there is no participant on these streets near the junction, the ego vehicle might continue at normal driving speed.

While increasing comfort in the aforementioned situations, up-to-date data can only be provided by the CEM if it has been reported by a vehicle recently. While lack of additional information only decreases comfort in those situations, other situations exist in which the ego vehicle depends on reliable additional data. For example, a traffic accident might lead to such a situation: Debris scattered on the street can make it difficult to choose the right lane. Additionally, involved rescue forces and tow trucks lead to repeated changes of lane availability.

To provide constantly updated data in such scenarios on demand, unmanned aerial vehicles (UAV) are employed as dedicated sensor carriers in UNICAR*agil*. Being able to move independently from streets and traffic, these so called Info Bees can arrive quickly at the site of an incident. Flying in the air, a unique point of view is provided without affecting the ongoing rescue operations.

Another use case for airborne sensors can arise in the aftermath of natural phenomena like storms, floods or earthquakes. For example, trees uprooted by storms can fall across streets, possibly blocking the street completely. This is problematic especially for rural streets because the resulting dead end can have a length of several kilometers. By deploying Info Bees after a storm to inspect the road network, such blockages can be detected quickly. Opposed to road-borne sensor systems, Info Bees can continue their inspection flights without having to take a detour caused by the detected closure. Information about the exact position of the blocking object is passed on to the cloud where it is taken into account during route planning. Also, cars with planned routes containing blocked streets can be provided with an alternative route by the cloud immediately.

3 Info Bee

With the advent of unmanned aerial vehicles (UAVs) capturing aerial images has become an easy task performed in many research projects [3][4]. In these projects, multicopter UAVs were used as they provide an easy way to lift a camera up into the air. Multicopters create lift through the downwash of their propellers, which are oriented in the horizontal plane. This enables them to hover as well as to take off and land vertically, so no special infrastructure like a runway is required.

This advantages come at a cost, as thrust-borne flight at higher speeds is inefficient compared to fixed-wing aircraft. Also, fixed-wing UAV typically have a higher maximum velocity therefore providing much longer range. On the other hand, fixed-wing aircraft generate lift with their wing moving through the air, and therefore require a minimum amount of aerodynamic speed. As a consequence, fixed-wing aircraft are unable to hover and require special infrastructure for takeoff and landing.

Correspondingly, fixed-wing aircraft are mostly used for inspection flights where observation shall take place along long distances while multicopters are employed in use cases in which several areas shall each be observed quasi-stationary.

Tiltwing aircraft combine the advantages of both aircraft types, efficient high speed flight and hover flight ability [5]. This type of aircraft is characterized by its ability to rotate the main wing on the aircraft's lateral axis. The Info Bee also rotates the tailplane, which is equipped with an additional engine, as can be seen in Fig. 2.

Fig. 2 Info Bee in both forward flight and hover configuration.

When the wings are oriented upwards, the propellers' thrust vectors face downwards whereby the aircraft behaves like a multicopter. In this configuration, the aircraft is able to hover and fly at low aerodynamic speeds. Because of the rotated wings as well as the slow horizontal inflow, forces and moments are created differently compared to the fixed-wing configuration: Thrust is mainly used to compensate for gravitation. Additionally, applying different thrust by the engines generates a moment around the roll or pitch axis. As the ailerons are overflown by the main propellers' downwash, aileron deflection results in a yaw moment. Horizontal movement is achieved by attaining small roll or pitch angles, thereby tilting the thrust vectors.

The center of gravity being located near the main wing requires the main propellers to generate most of the hover thrust. Therefore, these propellers are optimized for hover flight, resulting in weaker performance at high speed forward flight. However, as the rear engine only has to contribute little during hover flight, its propeller is designed such that it is able to efficiently generate all the required thrust during forward flight, allowing the main engines to stop and fold their rotor blades back at high speeds. [6]

3.1 Flight Control System

The onboard flight control system is mainly composed of two parts: All tasks immediately involved in the closed-loop control of the aircraft are performed on a microcontroller based autopilot system called “FluCo”. More sophisticated tasks, e.g. trajectory planning, are performed on the “HL-Board”.

The FluCo contains three microcontrollers each serving a distinct domain:

- The navigation domain employs sensor data to estimate the aircraft’s current state, e.g. position and orientation. Used sensors include a high-precision satellite positioning receiver (RTK GNSS) and 3-axis accelerometer and gyroscope. Additional sensors allow for continued state estimation even during external jamming of GNSS signals.
- The estimated state is used in the controller domain to calculate control commands in order to follow the given flight trajectory. This domain is the only one to have a connection to the HL-Board. Over this connection a new trajectory can be commanded. In reverse direction, the status of the aircraft as well as certain controller signals are reported back periodically in order to be accounted for during mission planning and for observation at the ground-based control station.
- The actuator domain transmits the control commands to the various actuators across the aircraft via a dedicated CAN bus. Also, it monitors actuator related states such as power consumption together with engine speed and temperature.

The central component of the HL-Board is a multi-core system on a chip (SoC), which allows for computationally expensive tasks such as planning of missions and flight trajectories. It is also equipped with two mobile communications modules and a backup satellite internet module providing a redundant connection to a ground-based control station. Furthermore, a FLARM module is included in order to make the Info Bee visible to other airspace participants as well as to receive their positions.

Because the HL-Board is way more complex than the FluCo, it has to be assumed that failure is more likely for the HL-Board. In order to achieve a high reliability of the overall system, the software components of the autopilot system are distributed among FluCo and HL-Board in such a way that the aircraft can operate autonomous. I.e., the Info Bee is able to follow the commanded trajectory up to and including the planned vertical landing even in case of a malfunctioning HL-Board.

3.2 Payload

The Info Bee is equipped with a visual camera. Because the aircraft’s orientation is predetermined by the commanded trajectory, the camera has to be alignable independently from the fuselage. Thus, a two-axis gimbal is required to mount the camera. In order to prevent additional drag, the gimbal is integrated into the fuselage structure. The nose section constitutes the first gimbal stage by being entirely pivotable on the longitudinal axis of the aircraft. Inside the nose section, the camera can be tilted on an axis that is parallel to the aircraft's lateral axis when the nose is rotated such that the camera faces downwards.

During long-range inspection flights, the aircraft will fly directly above the observation path. Hence, ±50° would be enough for the nose's rotation range. However, when circling above a fixed observation point, the rotation of the nose not only has to compensate for the roll angle Φ, which is required to create the centripetal force. It has to roll even further in order to point the camera onto the center of the circle. Hence, the nose section is designed to rotate through ±80°.

Integration of the payload components into the flight control system is achieved through a dedicated microcontroller board. This Payload Remote Unit is connected to the CAN bus of the actuator domain, such that target gimbal angles can be commanded from the controller. It is also connected to the navigation domain CAN bus, thereby receiving information about position and orientation of the Info Bee. Through a dedicated wire, the Payload Remote Unit triggers the acquisition of camera images, thus synchronizing exposure with calculation of the camera's position and orientation. Following, the resulting data gets transmitted to the payload computing module where it is combined with the corresponding image.

4 Path Planning

Information shall be gathered by the Info Bee as quickly as possible. Hence, the Info Bee should fly at the highest speed possible. Also, energy efficiency relative to both time and range is higher during airborne cruise flight compared to thrust-borne flight at slower speed. However, as the maximum roll angle attainable by the aircraft is restricted, so is the minimum turn radius the aircraft can track in cruise flight. A strong constraint on turn radii is imposed by inner-city streets with high curvature. In order to mitigate this conflict, a three-step method is presented. A more detailed description of this method can be found in [7].

First, the course of the street segments to be observed is approximated by line segments, thus smoothening out many small changes of direction. Second, the junctions of adjacent line segments are rounded by inserting circular segments with radii as big as possible while still covering the underlying street segments. Third, special turn maneuvers are introduced for those turns still possessing too small radii to be followed in cruise flight.

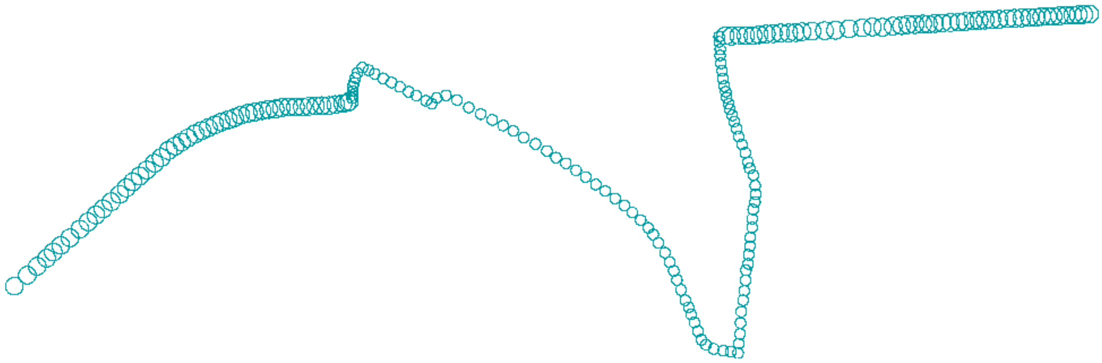

Fig. 3 Discretized example street course. Circles denote both the position of the center line and the width of the street.

To describe these steps in more detail, the street course depicted in Fig. 3 is examined. In this figure, the course has already been discretized as displayed by circles. Each circle is placed on the street's centerline while its diameter equals the width of the street at that position. Therefore, the tangents between adjacent circles approximate the roadsides.

In the first step, the point series is approximated through line segments. Starting with the first two points, linear regression is used to calculate a line for which the sum of quadratic distances of the center points is minimal. The result is depicted by the solid line in Fig. 4. The two dashed lines represent the borders of the viewing area along this line segment while the dotted lines indicate the width that would be needed in order to map all points. Since many more points are already inside the viewing area than taken into account for the calculation of this segment, another iteration is made in which these points are also considered. The result already covers all points, however another iteration with all covered points yields a better approximation resulting in a thinner required width.

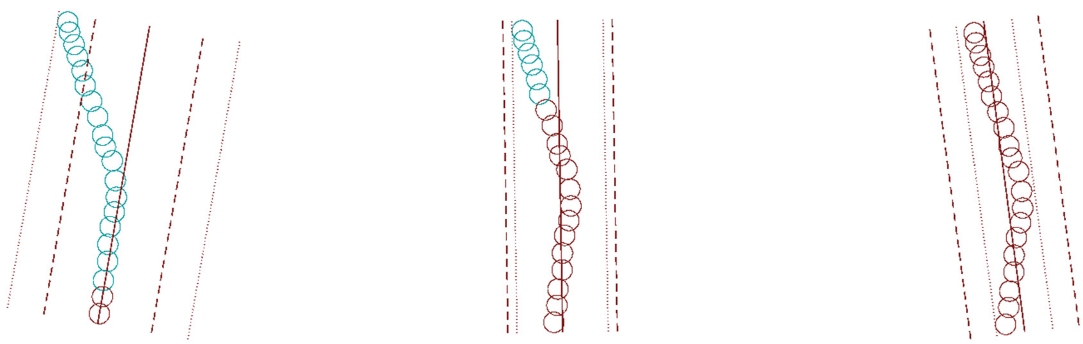

Fig. 4 Line segments determined through linear regression. Brown circles denote the points taken into account for the respective iteration.

In Fig. 4, all given points can be covered by one single segment. In larger sequences like the one from Fig. 3 iteration for a line stops as soon as the resulting segment is unable to cover more points than the previous one. Following, the creation of the next line segment starts from the last covered point. The resulting line sequence is displayed in Fig. 5. By using the entire width of the camera's viewing area, the line based observation path does not have to follow the sharp turns around the first third of the course. Instead, these can be replaced by one moderate direction change of about 60°.

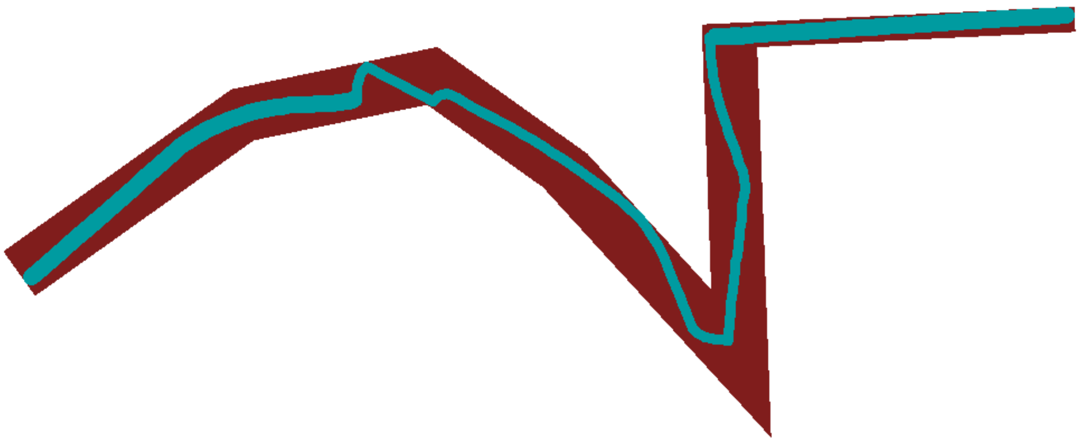

Fig. 5 Observation line sequence approximating the given street course.

Although the observation path is smoothened it is impossible to be followed exactly at high speeds. Because direction changes unsteadily at each intersection, the aircraft would have to attain very low speeds at these points. Therefore, circular segments are inserted. In order for the resulting radii to become as large as possible, consecutive turns in the same direction are regarded as one turn. If no circular segment can be found such that each point between the first and last considered intersection is covered by the circular segment or the first or last involved line segment, the calculation is repeated without the last intersection. In Fig. 6 it can be seen that the second and third change of direction are replaced by one single turn. While this step leads to high turn radii for the first two turns, the last two radii are only about 15 m, for which the Info Bee would have to decelerate down to 12 m/s.

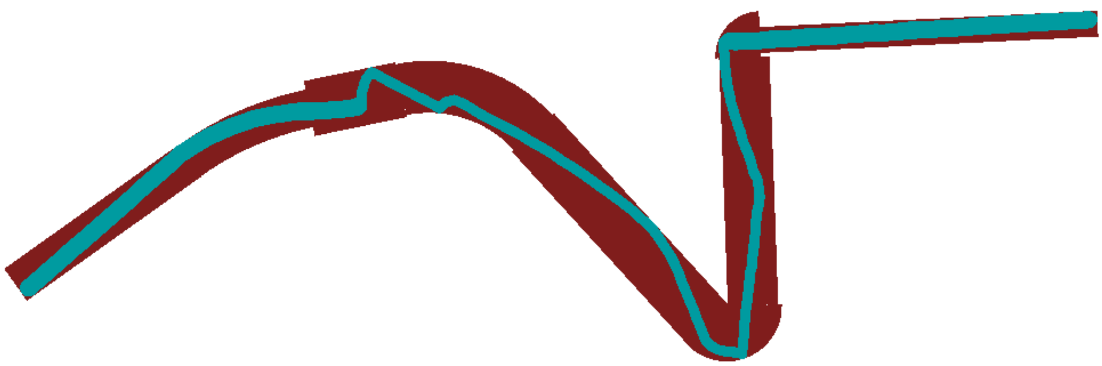

Fig. 6 Observation path with circular segments.

To prevent this situation, two alternative turn maneuvers are suggested, both of which achieve the direction change by rotating the other way round. The first variant, pictured in the left part of Fig. 7, is a special case of a Dubins path and therefore guaranteed to be the shortest possible path connecting two points with given directions [8]. When starting and end point coincide, the resulting path consists of three circular segments with the same radius and alternating sense of rotation.

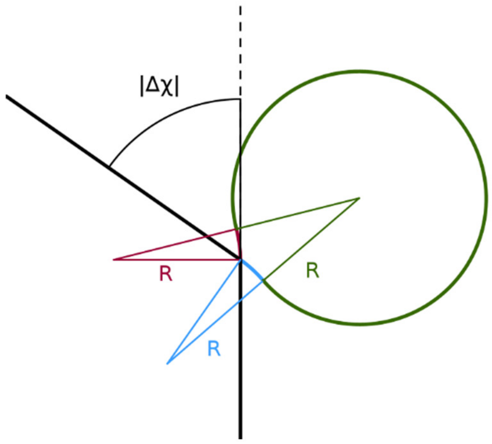

Fig. 7 Different turn variants for sharp turns. Left: Dubins path built with 3 circular segments. Right: Prolongation of the line segments connected through a single circular segment.

The length of the path is proportional to the radius, and therefore decreases quadratically to the reduced speed. Therefore, time required to follow this maneuver is reciprocal to flight speed. However, the more the speed is reduced, the longer the Info Bee has to decelerate on the line segment leading to the intersection and accelerate again after completion of the maneuver, thereby increasing the required flight time to some extent. Thus, optimal speed depends on the angular value of the change of direction, as displayed by the blue line in Fig. 8.

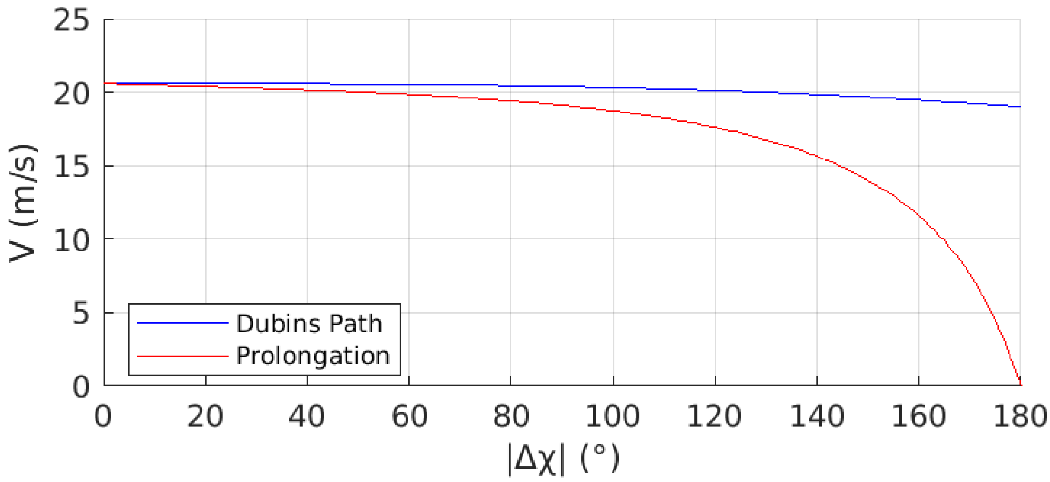

Fig. 8 Optimal speed as function of the angular value of the direction change.

For low angular values, the direction change is accomplished in less time by using the maneuver displayed in the right part of Fig. 7. Although this maneuver adds more way to the flight path, the distance to be covered at the slow turn speed is shorter compared to the Dubins path variant. Also, this maneuver is easier to track as only one turn is needed compared to the three immediately connected turns of the Dubins path.

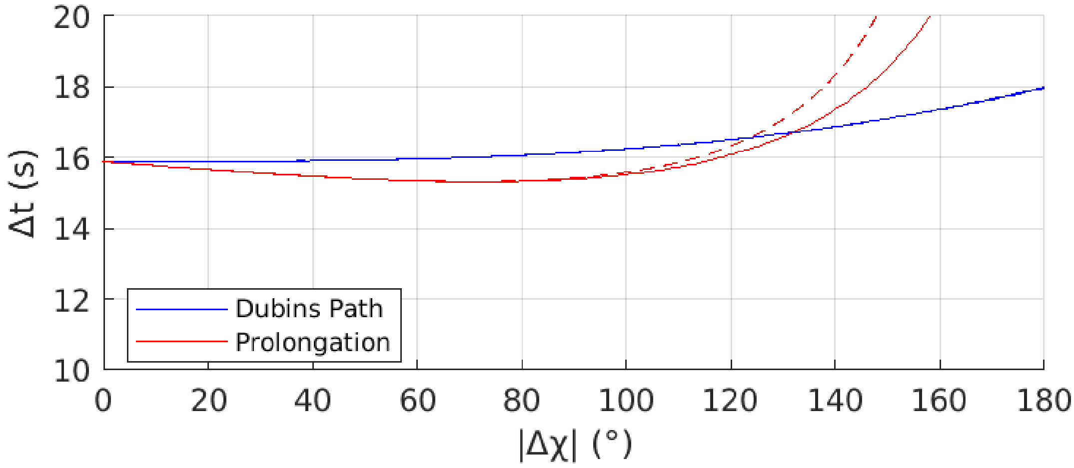

Fig. 9 Time required for the maneuver variants. The dashed lines denote the required time for a minimum speed of at least 20 m/s.

Fig. 9 shows the additional time needed for each maneuver compared to the theoretical case in which the line segments are followed at maximum speed without stopping or decelerating at the intersection. The alternative maneuver with extended line segments requires less time for direction changes up to about 120°. For higher angles, the extensions grow rapidly as their length is proportional to the arctangent of the half angle.

For the last two turns of the example path with angular values of about 135° and 90°, the optimal maneuvers therefore are Dubins path and prolongated variant, respectively, as can be seen in Fig. 10.

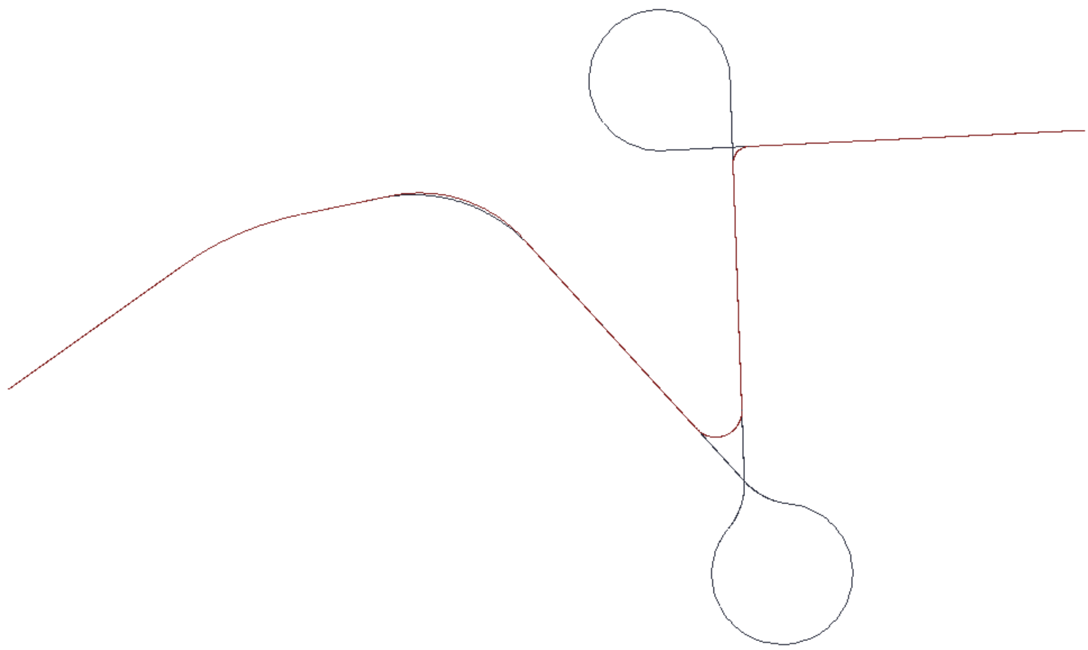

Fig. 10 Resulting flight path with Dubins maneuver for third turn and prolongated line segments for fourth turn.

5 Conclusion and Outlook

In this paper, we presented an approach to provide additional traffic information by using an airborne sensor system, the Info Bee. By using a tiltwing, the Info Bee is able to cover long distances at high speeds, thus collecting requested data as soon as possible, while also being able to hover over a specific incident site. Also, vertical take-off and landing allows the Info Bee to be based inside the city, thereby reducing the time required to arrive at a desired location.

Because high curvatures of the street segments to be mapped would require the aircraft to reduce its speed, we introduced a path planning method that creates a flight path which can be followed with a desired minimum speed. Using the viewing area being much wider than most streets, we first smoothen the street course by approximating it through observation line segments. The resulting intersections are rounded using circular segments. In order to limit deceleration for remaining sharp turns, two special turn maneuvers can be inserted.

In the current concept, data gathered by the Info Bee is used in order to inform vehicles about blocked roads or lanes. In addition to comfort related functions, the Collective Environment Model can also provide a vehicle with safety critical information, e.g. about other cars approaching an intersection on a collision course. In order to include data collected by the Info Bee into such safety critical information, both data transfer and image analysis need to be tested and verified extensively.

6 Acknowledgment

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