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PATH PLANNING FOR ULTRALIGHTS UNDER EMERGENCY CONDITIONS

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Abstract

The aim of this work is to design a path planning algorithm for ultralights under emergency conditions, mainly in engine failure situations. The pilot priority in such situation is to locate emergency landing site and perform landing. This article describes a method which is able to plan the flight path from the current aircraft position to the landing site. The flight path is planned with respect to the airplane kinematic model and aerodynamic limitations. The path planning algorithm is inspired by the RRT (Rapidly-exploring Random Tree) method.

1 Introduction

Approximately 69 percent of all aircraft accidents in Europe in 2012 fall under the cathegory of light airplanes, which is the cathegory this work is focused on. The most often accident reason is loss of control during flight, follows low altitude operation, fire post impact, control flight into terrain and weather conditions. [1] Almost all (except the fire) accident causes can be easily manageable with a computer since the glass-cockpit system enables pilot to see the terrain also in unsuitable weather, remember emergency runways and plan flight path with safety manoeuvres.

This work is a part of Emergency Landing Assistant, the computer-based electronic device designing at Czech Technical University in Prague [2]. The Emergency Landing Assistent is intended to support a pilot of ultralight under emergency conditions. This work is focused on the ultralight path planning in situations with engine failures. In this work the algorithm for the non-linear non-holonomic aircraft model with engine failure is proposed.

This work is split into eight sections. Related works are mentioned in the section 2. Section 3 summarizes the RRT algorithm. Trajectory constrains and an aircraft model requirements are described in the section 4. The Kinodynamic model of the aiplane and pilot is depicted in the section 5. The planning algorithm based on the aircraft and pilot model is introduced in the section 6. The used heuristics and designed algorithm parameters are described in the section 7. The demonstration result is illustrated in the last section 8.

2 Related Works

Similar works of last years are usually focused on a shortest flight path planning for unmanned aerial vehicles (UAVs). The main problem which these articles solve is time-efficiency and fuel consumption. This article is devoted to airplanes with limited flight range, which cannot be bigger due to altitude and smaller because of the airspeed limitations. Significant number of related works focuses on artificial intelligence algorithms, which are mainly genetic algorithms. [3][4][5] These works usually deal with UAVs and the planned path is parameterized as a spline curve. The flight path parameterized only by a sequence of headings (line segments) and transitions between them (turnings) is more suitable for human controlled aircrafts since it can be represented with only one parameter in the horizontal plane. Keeping a constant heading is a natural and easy task. Similar problems are discussed in [6][7], where the Dubin's car model is used. The reference [6] utilizes RRT algorithm and dynamic car model. The work [7] comes with Accelerated A* algorithm improvement for UAVs.

In 1998 LaValle introduced Rapidly-exploring Random Tree (RRT) algorithm [8] for motion planning. This algorithm was later (2011) extended by Karaman and Frazzoli [9]. This work proposes optimal RRT* algorithm. Both, the RRT and RRT*, algorithms are suitable for motion planning of holonomic kinematic models. The algorithm for kinodynamic planning of non-holonomic systems was introduced by LaValle in [10]. The introduced RRT for kinodynamic models is limited on the systems where motion planning between any two states from configuration space exists. In other words there has to exist a method which calculates a trajectory between two states of the system and an appropriate driving.

None of all the previous works is focused on the motion planning for non-linear non-holonomic systems with unknown inverse kinematic description.

3 Rapidly-exploring Random Tree

Rapidly-exploring Random Tree (RRT) was designed as an incremental sampling search algorithm. The main advantage of the RRT algorithm in comparison to conventional roadmap planners is in the rapidity. The algorithm is depicted in Algorithm 1. The idea is to sample configurational space with a sampler. The RRT is an iterative algorithm with five steps in each iteration. Before the iterations are instigated, a tree is initialized with one node of a prospective path. In the first step a random sample is selected from the set of space samples. In step 2 algorithm determines the nearest neighbor of the selected sample. The nearest neighbor is selected from the tree. In the step 3 an input driving the system to the neighbor sample is found. Next step executes the system simulator which is driven by given input from the neighbor sample for a defined interval. In this step the path segment is gained. The tree is extended by the path segment and the final node of the simulation.

This algorithm was introduced [10] for kinodynamic systems with known inverse kinematic description.

Algorithm 1 Rapidly-exploring Random Tree

procedure GENERATERRT($x_{init}, K, \Delta t$)
    τ.init()
    for $k \leftarrow 1, K$ **do**
        $x_{rand} \leftarrow$ RandomState()
        $x_{near} \leftarrow$ NearestNeighbor(x_{rand}, τ)
        $u \leftarrow$ SelectInput(x_{rand}, x_{near})
        $x_{new} \leftarrow$ NewState($x_{near}, u, \Delta t$)
        τ.addVertex(x_{new})
        τ.addEdge(x_{near}, x_{new}, u)
    end for
    return τ
end procedure

4 Trajectory Constrains

The operational space of the aircraft is limited by the aircraft's flight range. The operational space is a cone with the peak in the current aircraft position and the radius depends on the altitude of the aircraft. This relationship is described by equation 1

$$r = h \cdot \mathrm{g}(v_{best}), \tag{1}$$

where r is the maximal radius which can be reached by gliding airplane, h is the initial above-ground-level (AGL) altitude, g returns a glide ratio for given airspeed and v_{best} is the aircraft airspeed of the maximal glide ratio. Height of the cone is the initial aircraft altitude h.

The goal state (emergency landing site) is within the aircraft emergency operational space. The operational space involves static obstacles. State vector is introduced in section 5 of this work.

The aircraft heading is controlled by its ailerons, the airspeed is not intended to be controlled explicitly. Expression 2 describes a roll angle constrain

$$|\delta| \leq \delta_{max} \tag{2}$$

and the airspeed contrain is described by the equation 3

$$v_{max} \geq v_{ias} \geq v_{fall}. \tag{3}$$

The δ_{max} is a maximal roll angle, v_{max} is a maximal aircraft airspeed and v_{fall} is a fall airspeed. The constrain 2 and 3 imply the minimal radius constrain 4

$$r \geq \frac{v_{fall}^2}{g \cdot \tan \delta_{max}}, \tag{4}$$

where g is the gravitation acceleration and r is the turning radius. Additionally we propose to respect the limitation 5 of an aircraft angular velocity ω

$$|\omega| \leq \omega_{max}. \tag{5}$$

5 Aicraft Model

The aircraft mathematical model is expressed by a set of commonly non-linear differential equations, which describe the aircraft kinematics. The model has an internal state and is controlled through model inputs. The model state vector consists of all values describing all the variables of the aircraft (e.g. airspeed, altitude), the inputs are a yoke angle and an air brake position.

5.1 Kinodynamic Model

The proposed aircraft model is described as a non-holonomic kinodynamic system in the horizontal plane. The kinematic part of the aircraft model is described by the equations 6, 7 and 8

$$\dot{x} = v \cos \psi, \tag{6}$$

$$\dot{y} = v \sin \psi, \tag{7}$$

$$\dot{\psi} = \frac{g}{v} \tan \delta. \tag{8}$$

Coordinates x and y is the aircraft location in the horizontal plane. Angle ψ is an airplane heading, g is the gravitational acceleration and δ stands for a roll angle of the aircraft.

The dynamic character of the airplane model refers to the speed of aileron configuration setup (equation 9)

$$\ddot{\delta} = -\tau\dot{\delta} + \tau\dot{\delta}_w. \tag{9}$$

The τ in equation 9 stands for the time constant of aileron setting and $\dot{\delta}_w$ is the required aileron setting, which is directly controllable by the yoke in an airplane cockpit. [11]

5.2 Pilot Model

Pilot's role in the system is to control the airplane based on commands given to pilot from the pilot's Emergency Landing Assistent. Therefore the pilot is in the system as a contoller with an input of a desired aircraft heading ψ and an output of the aileron position $\dot{\delta}_w$.

Pilot tracking transfer function is taken over from [12] and in differential form is shown in the equation 10

$$\dddot{\delta}_w = \tau_p \ddot{\delta}_w + \dot{\delta}_p. \tag{10}$$

Overall pilot-aircraft system schema is depicted in the figure 1. The schema illustrates the relationship between the pilot and the airplane.

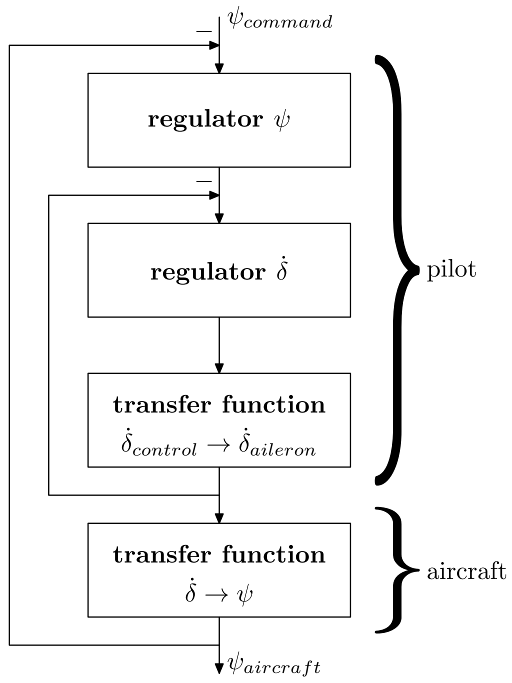

Fig. 1 Role of Pilot in the Controlled System

6 Informed RRT

The Informed RRT algorithm proposed in this work tends to maintain the RRT rapidity and provide motion planning for systems without a necessity of having an inverse kinematic description.

The algorithm is depicted in Algorithm 2. The Informed RRT does not sample the configuration space to obtain local target states for a local planner. The required behavior of the Informed RRT is guaranteed by the state selection and extension methods.

The Informed RRT is iterative with four steps. In the first one the state from the current tree is selected. In the second step the driving of the system is calculated. The system is driven in next step until it is terminated by predefined stop-conditions. In the last step the tree is extended by the path segment and the final state of the path segment.

Algorithm 2 Informed RRT

procedure INFORMEDRRT(x_{init}, x_{goal}, K)
    τ.init()
    for $k \leftarrow 1, K$ **do**
        $x_{rand} \leftarrow$ SelectState(τ)
        $u \leftarrow$ CalculateInput(x_{rand}, x_{goal})
        $s \leftarrow$ Simulate(x_{rand}, u)
        $x_{new} \leftarrow$ LastState(x)
        if ObstacleFree(s) **then**
            τ.addVertex(x_{new})
            τ.addEdge(x_{rand}, x_{new}, u)
        end if
    end for
    return τ
end procedure

6.1 Motion Primitives

Since the aircraft model is focused exclusively on the horizontal plane, the motion primitive set does not involve any altitude correction to optimize the planned trajectory. Three motion primitives were proposed to be used by Informed RRT algorithm: 1) Straight Flight, 2) Left Turning and 3) Right Turning. The resulting flight path is a combination of only these three motion primitives and the transitions between them.

6.2 Motion Primitive Selection

Motion primitive selection task is a part of function CalculateInput and is executed in each Informed RRT iteration. Based on the emergency landing recommendations [13] the motion primitive selection process is described by the Time Inhomogeneous Markov Chain. The transition matrix $P(t)$ (11) represents transition probabilities for all the motion primitives and the initial state

$$P(t) = \begin{array}{cc} & \begin{array}{cccc} s_0 & s_1 & s_2 & s_3 \end{array} \\ \begin{array}{c} s_0 \\ s_1 \\ s_2 \\ s_3 \end{array} & \begin{pmatrix} 0 & 0 & 0 & 0 \\ 1 & p_{11}^{(t)} & p_{12}^{(t)} & p_{13}^{(t)} \\ 0 & p_{21}^{(t)} & \ddots & \vdots \\ 0 & p_{31}^{(t)} & \cdots & p_{33}^{(t)} \end{pmatrix} \end{array}. \tag{11}$$

The s_1 represents the straight flight state, s_1 and s_2 are turning states and s_0 stands for an initial state. The $p_{ij}^{(t)}$ is a probability of transition from state s_i to state s_j in time t. The transitional probabilities change in time is based on an application metric.

6.3 Node Selection and Extension

The function SelectState implements a tree-node selection for a prospective extension. In RRT the node is selected randomly. In the Informed RRT we propose to calculate a selection probability for each node. The node will be selected with the calculated probability.The selection probability p_k of node k is defined (12) as a weighted average

$$p_k = \sum_{i=1}^{n} w_i f_i(k), \tag{12}$$

where n is a number of all features in the probability function, $w_i \in [0, 1]$ is a weight of i-th feature and f_i stands for a feature function, which could be e.g. heuristic or statistic function.

There is an extension method of the selected node for each motion primitive. Since it is possible to split the proposed motion primitives into two groups: 1) straight flight and 2) turning, two extension methods are designed.

6.3.1 Straight Flight Motion Primitive Extension

The rapidity of Informed RRT resides in the Straight Flight motion primitive extension. The tree using this primitive is not extended by only one node-edge pair, the sequence of several node-edge pairs is added to the tree in each extension execution. This behaviour ensures the rapid growing of the tree.

6.3.2 Turning Motion Primitive Extension

The extension using Turning motion primitive is parameterized by the heading change $\Delta\psi$ argument. To each possible heading change corresponds a probability of the selection. The probabilistic distribution is defined by the function h with the limitation 13

$$\int_{-\pi}^{\pi} h(\phi) d\phi = 1. \tag{13}$$

A heuristic used for the function h is defined in the section 7.

6.4 Model Simulator

The model simulator is a module which performs the differential equation solving (system simulation). The simulator works with the aircraft model given by the set of diferential equations and for a given input simulates the system behavior. The simulator execution is terminated when given conditions are fulfiled.

7 Emergency Landing Application

In this section the heuristics used in the Informed RRT for emergency landing purposes are described. This section is devided into two parts.

7.1 Motion Primitive Selection

The probabilistic distribution h (13) is in the application of emergency trajectory planning defined (14) as a multiplication of Gaussian g_n with the mean in the direction of the goal state and the distance-to-obstacles function d_n

$$h_n = g(\Delta\psi_n, \frac{\pi}{6}) \cdot d_n. \tag{14}$$

The n is a node index, $\Delta\psi_n$ stands for the angle between node heading and heading to the target. The function d_n returns a normalized distance to the nearest obstacle in each direction.

7.2 Node Selection

In this application two feature functions f_i were defined (12). Function f_1 is defined (15) as

$$f_1 = ||\max(d_n) - s|| \cdot ||d||, \tag{15}$$

where s is a vector of the goal state. Function f_2 is a sum of all edges starting in the node.

8 Results

Proposed Informed RRT algorithm was successfully applied to the airplane navigation problem. The result of 350 algorithm interations is shown in the figure 2. The red stars stand for the start and the goal. The figure 3 depicts the same approach with the limited rapidity character in a comparison to the previous result. The roll angle is limited by the interval $\phi \in [5, 30]$ deg, maximal turning is limited by 180 deg and the straight part of the flight in the figure 2 is six times larger than in the figure 3.

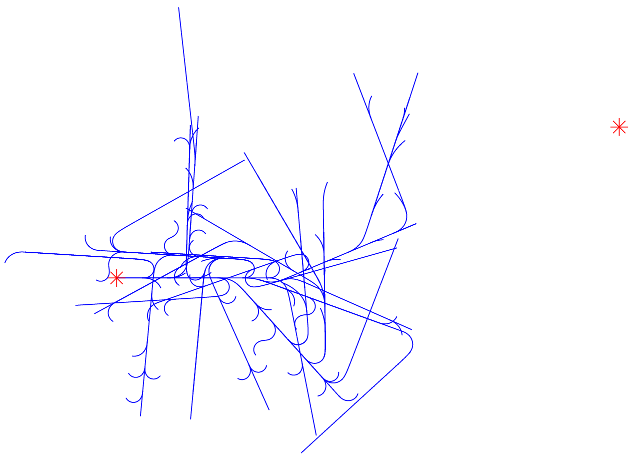

Fig. 2 Informed RRT After 350 Iterations.

The proposed algorithm was tested with nonlinear aircraft model in the simulation of a gliding. This method succesfully search for a flight path with keeping the rapidity character.

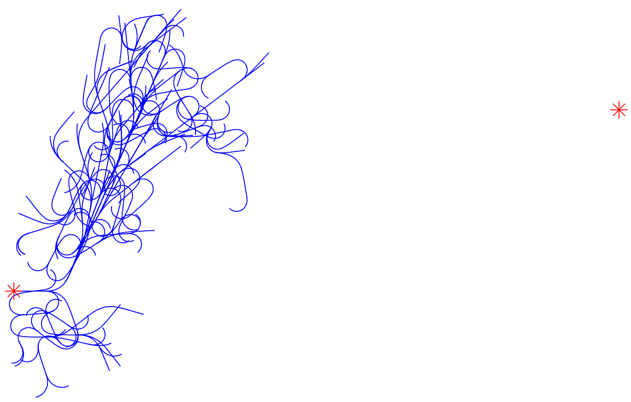

Fig. 3 Informed Approach Without RRT Characteristic After 350 Iterations.

9 Summary

The Informed RRT method with the airplane model is used for the ultralight flight path planning in emergency situation. In such situation a flight range of an aircraft is limited by altitude and airspeed. This application is not common and helps to increase air traffic safety. The method tends to be an extension of glass cockpit system for ultralights and help pilot manage emergency landing.

The proposed method combines behavior of the RRT algorithm with the kinodynamic system without a necessity of having an inverse kinematic description. The proposed method is not general, but it is available for many vehicle motion planning tasks.

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