

# SMALL AIRCRAFT EMERGENCY LANDING DECISION SUPPORT SYSTEM – PILOTS' PERFORMANCE ASSESSMENT

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**Abstract:** This paper describes the methodology for investigating the usability of an emergency landing decision support system for ultra-light aircraft pilots. The introduction covers the aim of the device, while section methodology describes what the goal was and how it was achieved. The evaluation discusses the interpretation of the data measured and interviewed outputs. This paper is concluded with our learning and suggests future work.

**Keywords:** Human factors, flight, pilots, testing, small aircraft, ultra-light aircraft, human computer interaction.

## 1. INTRODUCTION

Pilots of small aircrafts are endangered by many events. The one responsible for many fatal events is an engine failure shortly after takeoff [1], [2]. As a result, pilots often perform manoeuvres that are very dangerous to them and the aircraft. For example they try to avoid landing on the grass or field by turning the plane back to the airfield. By doing so the aircraft loses lift and falls to the ground much faster resulting in the death of the pilot. The system designed at the Czech Technical University in Prague helps the pilots to solve these emergency situations by giving them instructions on where to land and how to approach alternate landing sites.

The intention of this paper is to propose a methodology for testing the first prototype of this decision support system. The purpose of the test presented in this paper is to determine the possible ways of improvement of the system in terms of usability and to confirm that current design is going in the right direction.

The final goal is to implement the system in onboard avionics and make it part of the standard equipment of aircrafts [3], [4].

Even though this matter has been addressed before [5], [6], [7], [8] it was aimed mainly for use in traffic or military aircrafts. This paper on contrary considers only small sport aircraft and ultra-light aircraft.

The system can be extended and used to avoid other airplanes or terrain [9].

## 2. EMERGENCY LANDING SUPPORT SYSTEM

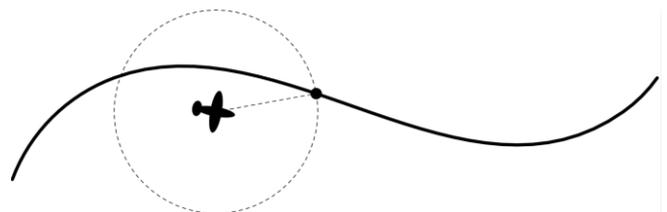
The system is designed to recognize an emergency situation caused, for example, by engine failure. In that case it maps the airplane's current position from GNSS (Global Navigation Satellite System) and compares it with a map

stored in its memory. Then it searches for possible landing sites and computes the distance the aircraft is capable of flying. Some landing sites may not be in the achievable flight range of the aircraft. The achievement does not depend just on the aircraft to runway distance but of course on the flight path length. The flight path could not contain too acute angles. Thus the flight path cannot be determined in advance, but the flight path should be checked whenever it is planned.

The landing site is depicted on the screen of the pilot's decision support system and leads the pilot to the landing site. The pilot can either follow the shown path or the path can be altered by pushing a button. The interaction with the system is a matter of future testing and is not included in this paper. Pilots can also decide to omit the system and to land on their own on a place of their choice. The system is not able to take into account unpredictable events, which may make the proposed landing site useless, so the pilot should always make the final decision.

The standard navigation command is represented in four ways: (1) by two crossing lines meaning how much the pilot should fly in an appropriate direction – lateral and longitudinal, aligned with the horizon (it will be referred to as cross rotated or simply cross), (2) similar concept, but with lines aligned with camera view (it will be referred to as cross nonrotated or n/R), (3) a dot which shows the same but has a small ball in the middle (will be referred to as point), and (4) a rectangular static tunnel showing borders of the flight path (highway in the sky).

The calculated flight path is stored as a sequence of line segments joined by arcs. In the area of unmanned aerial vehicles are usually used splines as flight path representation. Spline curves are more natural and really suitable for flights. However the line segments and arcs are



*Figure 1: Navigation command.*

more suitable for the purposes of man-controlled flight because they can be represented just by one parameter during the flight – heading or bank angle. Hold only bank

angle or heading at certain position is commonly very simple and it does not cause problem to the pilot. Thus the pilot should do just usual manoeuvre which leads to safer flight without redundant stress. Both geometrical shapes used, are represented by typical points. In case of line segments the characteristic points are both marginal points and for arcs central starting and ending points are used.

The task of a navigation algorithm is to calculate and display the command to the pilot. Principally it is the informational feedback, and its aim is to minimize the flight path error. The command should be continuous, but it is not directly the flight path error because of not-suitable dependence on the pilot's action.

Before the navigation command is calculated, the meeting point should be determined. The meeting point (see Fig. 1) means intersection of the desired flight path and a circle with a position of the aircraft in its center. The command is then computed as a heading error – the difference between required heading to the meet point and the current heading of the aircraft.

A meeting point can be determined as an intersection either of a circle and a line segment or a circle and an arc, so it can be solved as a set of two second order equations. Because more intersections exist, the algorithm remembers the current part (geometrical shape) of the flight path and selects only the nearest meeting point in the direction of desired flight path.

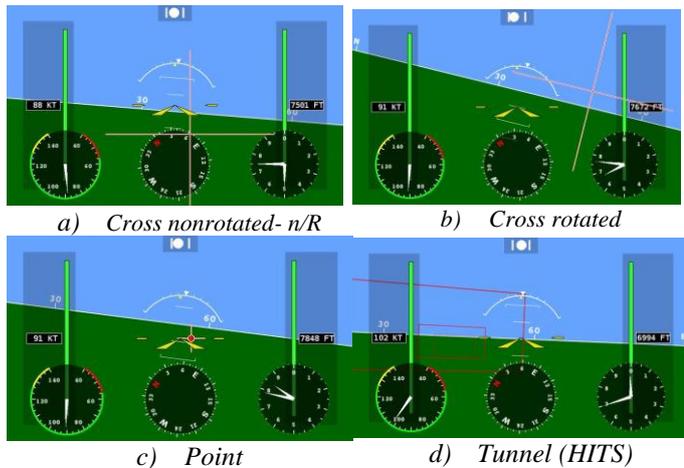


Figure 2: Flight directors – guidance markers.

### 3. PILOT NAVIGATION COMMAND

As it was mentioned above, the navigation algorithm calculates so-called meeting point – intersection of desired flight path and circle around the current aircraft position. The circle radius is determined as a set of possible positions where the airplane could be in certain amount of time. The circle radius is function of time parameter which should be varied to determine “the right value”. This time constant was adjusted under pilot testing and it is the main parameter for the navigation module.

Determined meeting point is an important part of the navigation procedure. This point is a virtual moving target of a small current flight part. The pilot should fly into this point. Since this point is moving toward along desired flight

path, pilot does the force feedback and makes the aircraft flying to the meeting point. This suggests dog's effort to chase a rabbit. Using the meeting point method has several advantages in comparison with evaluation of heading or flight path error. The first idea was to show linear combination of heading a flight path error to the pilot. The only problem in the linear combination is to weight both of used parameters. Only the heading error reducing leads to increasing the distance from desired flight path. On the other hand reducing only flight path error is not natural and does not respect the direction of flight. This kind of navigation makes airplane oscillating around the desired flight path. The linear combination of both of these parameters is really inappropriate because they have opposite divergences. In certain circumstance of the desired path exists a combination of the distance and heading which is equal to zero. Weighing these two parameters changes behaviour but measuring shows this method as unsuitable.

The command to pilot has two components – the vertical and the horizontal one. Both parts of the command are calculated separately from the knowledge of meeting point and aircraft position. In horizontal direction is shown the angle difference between the meeting point course and heading of the flight. This small error is simply controllable to zero. In vertical direction could be also displayed angle deviation but then the device should know climb angle of the aircraft in a short time. According to this problem it seems to be easier and still suitable to use a vertical distance between the meeting point and aircraft position. In small deviations the dependence stays linear, since the small climb angles are usual.

### 4. METHODOLOGY FOR TESTING

The findings we are interested in are (1) the parameter corresponding to the constant time flown by the aircraft (which is equal to the radius of the circle used to calculate the meeting point), and (2) test which of the four markers are best to use in terms of performance.

FlightGear simulator is proposed to simulate the flight; according to [10] it appears to be the most convenient way of testing. It is an open source simulator with possible additions. This program is connected via a virtual connector to the decision support system. The test can be carried out on the ground in a testing room equipped with a computer and a simulation program simulating aircraft Cessna c172p. Two screens plugged into the computer will ensure the display of scenery and other flying instruments needed. Secondary monitor will display the tested instrument as well. More complex tests are conducted on the ground in team's research facility using the motion flight simulator (Figure 3: Motion simulator for tests.).



Figure 3: Motion simulator for tests.

To address the first problem, subjects are requested to follow the flight path with the highest possible precision for different parameter of radius and for different reaction speed represented by parameter P. Each subject is given multiple flight missions and each pilot starts with different setting to mitigate the learning effect. Preliminary results are presented in Table 2. This qualitative tests result in a hypothesis saying which parameters are best to use.



Figure 4: Operator station.

To address the second issue two rounds of one-by-one tests are proposed.

The first round is performed on a group of people, who had no actual flying experience. Each mission's objective will be to follow the predetermined path displayed on the screen of the instrument. Four different markers will be used in different order to avoid bias caused by learning how to fly. Subjects' performance will be evaluated from recorded data from FlightGear, which records the error of the subject. We intend to create a hypothesis determining the marker giving the best comfort. The focus is on the point of view and usability of markers. Interaction is not an issue here.

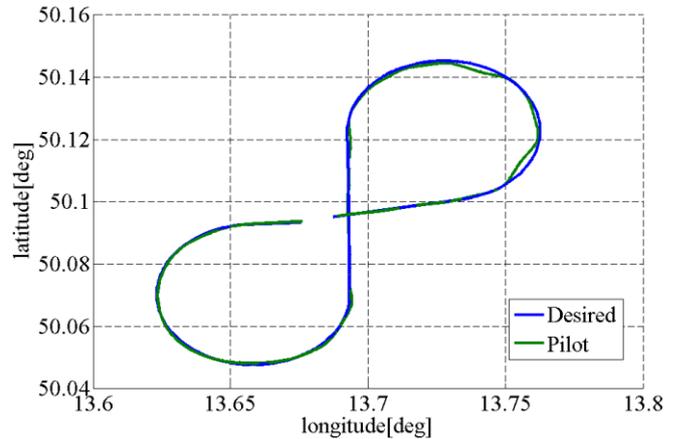


Figure 5: Flight path from top view.

Second test (qualitative form) will be focused on use of the program in the emergency situation. The sample will be pilots of light sport aircraft with enough experience. The subjects will be given 4 flight missions. Objectives will be again to land the plane, but this time using the motion simulator. The flight will be simulating an emergency landing. We wish to create a hypothesis saying under which tells how is pilots' performance affected by used interface.

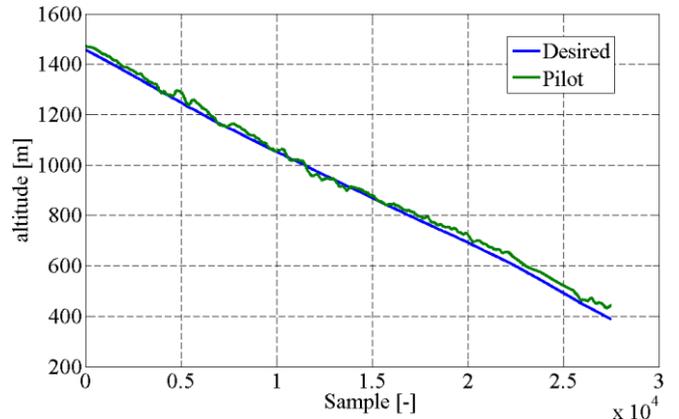


Figure 6: Desired flight path altitude compared with a real flight.

Following data are recorded during the simulation: speed, location, altitude above ground level and flight angles.

## 5. USABILITY TESTING

This section describes how the methodology was implemented and how the tests were conducted. The usability testing was always performed in a one by one manner. There were two rounds of usability tests: (1) naive subjects, (2) professional pilots or pilots of small sport aircraft and of other aircraft (gliders).

The first group was tested using computers. Second sample - pilots were tested with the motion simulator.

The first group were 4 randomly chosen subjects who were tested using computers. They were given a task to follow the flight director as possible as they could and after all the flights were done, recorded data were processed using computational program and each subject was interviewed in terms of comfort and complexity of the task.

The second group included 5 pilots: there were three pilots with flying experience of less than 100 hours (PPL - professional pilot license), one pilot with flight hours in between 101-400 (ultra-light aircraft pilot license), one pilot with over 3640 flight hours (glider license, ATPL – air traffic pilot license). Age of pilots was between 21 and 30.

Each session started with a briefing explaining the structure and aim of tests. Afterwards the pilot entered the simulator and went through a test flight, which aimed to get pilot familiar with behaviour of the simulator and to learn how to control it. When the pilot managed to deal with the simulator, first navigation flight out of four could start. There were four flights to test all four navigation markers (flight directors). The order of flight scenarios was chosen randomly.

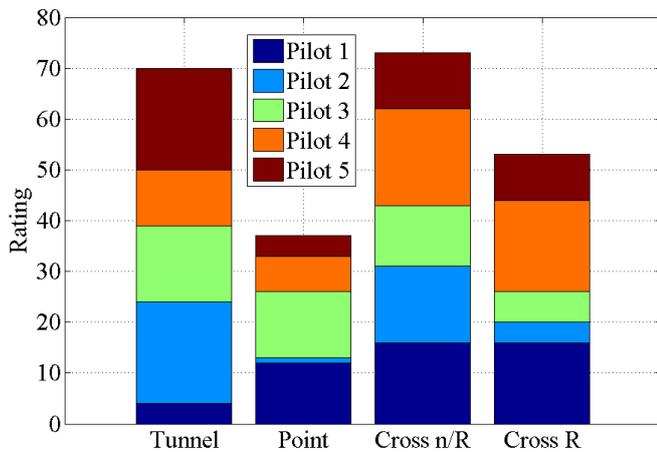
During the flight, the pilots were given a task to follow the predetermined path as precisely as possible according to the flight director.

Following each test, pilots were given NASA TLX (task load index) questionnaire to evaluate their load. The questionnaire rates the different aspects of task on a scale from 1 to 20. The lesser the rating is the better. It focuses on six different aspects: mental demand (M), physical demand (Ph), temporal (T), performance (Pe), effort (E), frustration (F). Results of rating are in *Table 1*.

Interface	M	Ph	T	Pe	E	F
Cross R	32	35	39	28	52	30
Cross n/R	37	30	32	18	45	31
Point	31	48	47	29	53	36
Tunnel	27	23	26	14	38	24

**Table 1:** Evaluation of flight director using NASA TLX.

After the last test flight, pilots filled in final questionnaire, regarding all the markers. Questionnaire asked pilots to rate quality of markers in terms of navigation usability. Rating ranged from 1 to 20 points, 1 meaning unsatisfactory and 20 meaning very satisfactory. Rating given by pilots is in *Figure 7*.



**Figure 7:** Rating of flight director.

The trajectory chosen for testing was not usual. The flight director was intended to lead the pilot from certain point on the map to the emergency landing site, but for testing purposes the scenario was different. Pilots started

with the aircraft flying and the navigation guided the pilot to airport. The flight route was not a standardized one. It had an eight shape as can be seen on *Figure 5*. That made it possible to evaluate the performance of pilots in left and right turn and in straight flight. Because the navigation system was leading the aircraft to the airport, the trajectory was constantly descending, see *Figure 6*.

The last step was interviewing the pilots. Pilots and subjects were asked to give their opinions on the matter and propose possible alternatives and solutions best suitable for them.

Pilots in the sample were chosen according to following filter.

## 6. INTERVIEWS EVALUATION

Interviews were conducted to provide insight into how pilots use the device and how they think about it. Beside interviews, also focus groups were conducted with the same aim. Another reason was to determine, if the concept is correct and to analyse possible changes and innovations. The main points from interviews and focus groups can be summarized as follows:

- Watching the screen can lead to decreased situation awareness.
- Tunnel shows trajectory in advance, which have been accepted very positively.
- The point is too small to be used for navigation purposes. Hard to find on the screen.
- Cross and point flight director considered are stressful, because it does not show the trajectory.
- Show the whole trajectory in advance.
- Larger tunnel squares.
- Useful show desired heading and miles to reach the location instead of using flight director.
- Using EFIS (electronic flight instrument system) in small aircraft is undesirable.
- Time to impact in case of engine failure estimated to minutes, which provides pilot with no time to interact with the device.

## 7. RESULT EVALUATION

From statistical frame of reference the results evaluating was done using a mean and standard deviation of measured quantities. A mean of the flight path error is used to determine how precisely a pilot can fly along a guidance line (flight path graphical projection). The flight path error standard deviation is important to determine how fast in advance the navigational algorithm should refresh the command markers to give to the pilot enough time to react. The flight path error is determined as Euler distance between aircraft's position and desired path. In case of line segment flight path, the error is calculated as shown in (1).

$$\Delta_{line} = \frac{|P-L_1| \times |P-L_2|}{|L_2-L_1|} \quad (1)$$

Where  $\Delta_{line}$  is a orthogonal distance from the point  $P$  to line determined by points  $L_1$  and  $L_2$ . All data samples were collected with sampling frequency of  $50\text{ Hz}$  – the data were obtained every  $20\text{ms}$ .

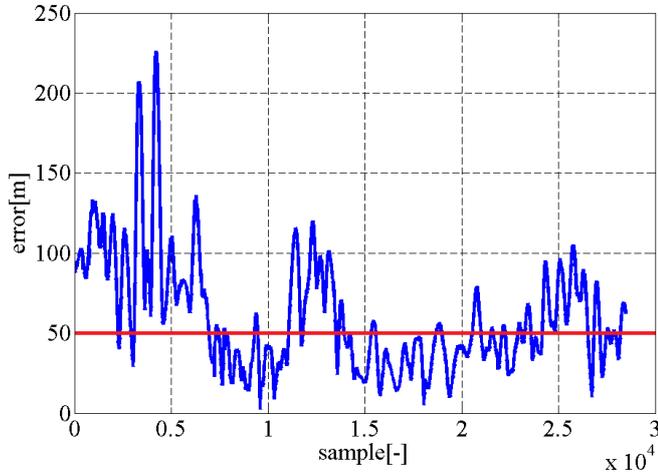


Figure 8: Flight path error as Euler distance.

For an arc flight path see the formula (2).

$$\Delta_{arc} = r - |P - A_C| \quad (2)$$

Where  $\Delta_{arc}$  is a shortest distance between a point  $P$  and an arc with a centre in point  $A_C$  with radius  $r$ .

Data presented in this paper are first measured data intended for determining the parameter of radius of the navigation.

Time [s]	P[-]	$\bar{\Delta}_{arc}$ [m]	$\sigma_{arc}$ [m]	$\bar{\Delta}_{line}$ [m]	$\sigma_{line}$ [m]
5,00	0,20	9,98	8,98	7,27	4,61
7,50	0,20	21,63	5,49	10,50	7,38
8,75	0,20	20,54	12,58	9,68	8,89
10,00	0,20	46,37	9,19	10,25	9,39
5,00	0,50	9,40	3,95	3,11	3,77
7,50	0,50	25,72	5,82	14,82	5,11
8,75	0,50	35,61	6,93	11,15	8,11
10,00	0,50	49,40	3,32	10,51	10,43
10,00	0,10	35,43	16,77	17,04	7,89

Table 2: Determining the time parameter.

To evaluate measured data in terms of pilot performance, several approaches are presented in this paper: (1) RMSE (root mean square error) (2) the performance is evaluated in terms of percentage out of flight envelope, which is similar to the TD (time of deviation) parameter, (3) ND (number of deviations), (4) MTE (mean time to exceed tolerance), as suggested in [4].

Interface	Mean[m]	Sigma[m]
Tunnel	61.28	5.49
Point	105.12	50.31
Cross rotated	86.60	31.29
Cross n/R	111.77	54.14

Table 3: RMSE evaluation of subjects' flights.

Data in Table 3 and in all other tables are referenced to the tolerance and flight envelope denoted by a cylinder around the flight path with radius  $50\text{m}$ . The radius and the error from the flight path is shown in Figure 8. The red line marks the tolerance. If the error is less than the tolerance it is considered acceptable flight performance. The RMSE was computed using Eq.3.

$$RMSE = \sqrt{E((\hat{\theta} - \theta)^2)}, \quad (3)$$

where  $\hat{\theta}$  is actual position and  $\theta$  is a desired position computed by the navigation assistant in meters. The results are noted in Table 3. Small RMSE is a sign of a good flight performance.

Interface	Subject1	Subject2	Subject3	Subject4
Tunnel	50.20	45.08	57.92	57.55
Point	62.13	70.42	81.77	92.50
Cross rotated	64.77	52.36	68.14	86.58
Cross n/R	79.63	70.40	80.36	99.04

Table 4: Percentage of aircraft out from flight envelope from the whole flight.

The data in Table 4 were computed using the Eq. (4):

$$OE = \frac{N_o}{N} \cdot 100\%, \quad (4)$$

where  $OE$  is percentage of the flight samples out from the flight envelope,  $N_o$  is a number of samples where the plane was out from envelope and  $N$  is a total amount of samples. The lower the number is the better the performance.

Interface	Subject1	Subject2	Subject3	Subject4
Tunnel	58	61	82	84
Point	82	113	58	8
Cross rotated	83	28	87	37
Cross n/R	50	44	54	4

Table 5: Number of deviations.

Number of deviations reflects how many times the pilot crossed the tolerance and flew with the aircraft to the forbidden region. Low number can mean both good and wrong flight performance. Data in Table 5 need to be read with data in Table 4 and in Table 6. It gives more complex idea of the pilot's performance. For example the Subject 4 has only 8 deviations, but spends most of the flight out from the envelope, so it is considered as unsatisfactory performance.

Interface	Subject1	Subject2	Subject3	Subject4
Tunnel	4.97	4.38	2.87	2.83
Point	2.54	1.47	1.74	3.69
Cross rotated	2.32	8.23	2.11	1.80
Cross n/R	2.35	3.34	1.66	0.35

Table 6: Mean time to exceed tolerance.

Data in *Table 6* are indication of pilot's ability to stay in desired tolerance. The greater the number is, the better performance.

## 8. CONCLUSIONS

In this paper we propose a methodology for testing the performance of pilots of ultra-light aircraft and present the preliminary measured data. The measured data are suggesting that larger radius has greater mean value and smaller variance. Large mean value means stable error, but steady flight. On the other hand small radius results in smaller errors but significant oscillations around the flying path.

Tested interface for navigation assistant tends to create hypothesis for further testing: the tunnel and the cross (non rotated) show the best results in terms of both subjective and objective evaluation.

Rotated cross and point failed to indicate potential to be used in the future and future interfaces will be developed without these alternatives.

Regardless the interviews pointed out some very important issues and possible innovations – since the pilot is not able to work directly with the screen and is not able to watch the screen of EFIS since ultra-light aircrafts are not allowed for IMC (instrument meteorological conditions), next generation of interface will take advantage of audio display and will provide information and guidance using sound.

The EFIS screen will be also used to show the flight path, but with the whole trajectory shown on the screen combined with flight director.

Future work will focus on verifying findings on larger sample and with next generation of instrument including sound display. Future work will also aim to propose a test to compare the performance of people flying under and without stressful conditions.

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