Flight reconfiguration system – an emergency system of the future

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Abstract

Purpose – This paper aims to describe the idea and partial result of research on flight reconfiguration system (FRS) which is to be used in case of pilot incapacitation while performing the single-pilot operations for defining and guiding an aircraft to a safe destination.

Design/methodology/approach – Multiple problems with the development of emergency systems which could deal with crisis on-board occurs, e.g. definition of emergency destination which is dealing with the thread, ensuring that route to an emergency destination is safe, avoiding of air traffic and making sure that aircraft performance limitations would not be exceeded. FRS is a sophisticated hardware design, gathering data from aircraft on-board systems, commanding autopilot where to go and informing air traffic on crisis on-board. Developed algorithm analyzes data from onboard systems, internal database to calculate potential safe places and best routes to them. Multi-criteria decision-making is used to choose the best of them and execute it when needed.

Findings – Algorithms and hardware were tested in a simulated environment. An exemplary research experiment oriented on finding emergency destination and flying to it in the Software-In-The-Loop environment was presented.

Research limitations/implications – Currently, the use of the system is limited to use on-board of well-equipped CS-23 class aircraft and is limited to use in good weather conditions.

Practical implications – The use of FRS will in case of emergency constitute a new category of emergency maneuver, used for dealing with no-human pilot available on-board situations – autonomous emergency destination finding and route execution.

Originality/value – This study helps in the introduction of multi-stage decision-making to autonomously reconfigure route.

Keywords Multiple criteria decision-making, RPAS, Flight control system, Aircraft emergency system, Multi-stage decision-making

Paper type Research paper

Introduction

Flight reconfiguration system (FRS) is a safety-related system, which is being silent (no data sending from FRS) in normal operating conditions. In case of an emergency onboard (e.g. human incapacitation), its task is to perform an emergency procedure. It is developed within the COAST project, being part of Clean Sky 2 which purpose is to develop cost-effective avionics that can be used onboard of CS-23 category aircraft. Investigation of the topic of automatic flight diversion management was the goal of many research projects so far. Example investigations can be found in the work of Rogalski and Krawczyk (2010) within Sofia Project, Fallast and Messnarz (2017) within the eSafe project. In presented systems, no considerations were published on the efficiency of algorithms against the database consisting of several thousand of possible destinations. Time to the delivery emergency solution was not that important or database was so small, that it was not a problem to handle by hardware. Such a consideration must be made for human health issues, where good practice is to meet with medics within 4 min for critical cases, and every second is significant. The main difference in approach from analyzed systems is that FRS is developed as a standalone module that can be used for existing aircraft by interconnecting it with onboard systems with ARINC 429 interfaces. It is designed to satisfy the design assurance level required by EASA for onboard systems. Moreover, a new approach in the decision-making process was developed to deliver FRS calculated routes on time considering hardware limitations and the possibility of application onboard of existing aircraft. Such limitation is given by the number of runways in the database which needs to be considered for finding an emergency solution (database used for the project consisted of over 13,000 runways). Path calculation for every possible runway in such a case will lead to a situation that a new route will not be delivered on time, so an effective selection method of potential airports selections must have been developed. Within the emergency procedure, FRS recalculates a new route to a safe

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place and commands autopilot to follow it. While performing this task, it automatically informs other airspace users and ATC on the emergency by transmitting appropriate transponder code. Route calculation is made using algorithms described in detail in the section about FRS algorithms. Description of FRS hardware with supporting software is made in the section related to FRS hardware.

Main section

Flight reconfiguration system algorithm

During a flight, continuous search for new possible emergency landing places is needed, as of situation changes in flight dependent on aircraft state (e.g. geographical position). To compare possible solutions and pick one best of them, they need to be fed with the same input data. Calculating the path to subsequent airports is considered to be the most time-consuming process when calculating emergency destination, and as such can lead to a situation that data for comparing first and last considered runway may be inconsistent because for calculation of last one input data on geographical position are obsolete. In general, three approaches can be considered for overcoming such a problem:

1 higher computational power to deliver answers on time;
2 simpler path planning algorithms, to reduce the time of calculation of single path; and
3 defining best premises airports and defining path only to those.

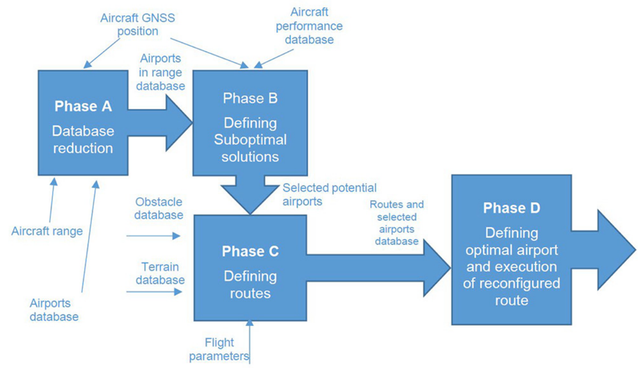
Main limitations of approaches can be defined as follows:

- Higher computational power for delivering solution leads to the usage of more complex systems, which are more efficient, but, on the other hand, more difficult to certify and less reliable.
- Simpler path planning algorithms will lead to the possible definition of conflicts en route which were not considered in the calculation (e.g. ground clearance), and hence reducing the margin of safety.
- Complex algorithm dependent on object state, where precise definition of criterions must be made, prior to picking of the best premises (not to neglect better solution or disregard them).

The third approach was explored when defining an algorithm for FRS. Such approach lead to development of multi-phase algorithm in which combination of phases leads to delivery an answer on time. Basic idea is to reduce set of all possible destinations only to those which for current flight conditions will be worth of calculating exact path. Next only for those for which paths are available, best solution for current state is picked. Time to delivery an answer is very important because to compare results most methods use same initial conditions. If that assumption does not hold, then chosen destination could be the one, for which route is obsolete. Figure 1 presents the developed algorithm which was divided into phases.

In phase A from all possible airports in the database, only those in a range of aircraft are passed to the next phases (reduced airport database is created). This is done to reduce the number of calculations of routes which are by definition out of range of airplane from a current geographical position. This is used as the first method to improve the performance of the

Figure 1 Flight reconfiguration system algorithm concept



algorithm. Moreover, because maximal range from start position is considered, this part of calculation can be performed while aircraft is still on the ground. In phase B, further reduction of the database is performed. At this stage for the first time in the algorithm, multiple criteria decision-making (MCDM) takes place. The purpose of this is to score and sort the most suitable airports for landing, taking into account aircraft performance and landing limitations and estimating the distance to the airports. For this purpose, the following criteria have been used:

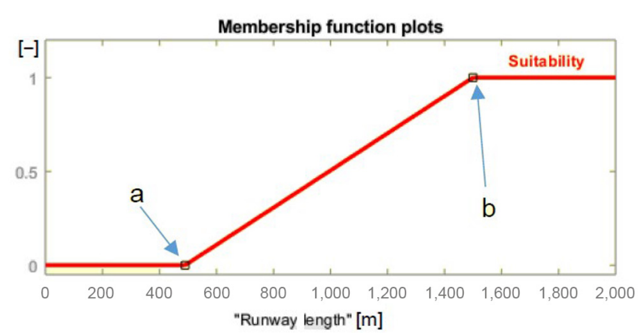
- runway length suitability;
- emergency services available; and
- estimated time to destination.

For defining runway length suitability membership function from fuzzy logic methods were used. Figure 2 shows membership function values dependent on runway length.

Point "a" defines minimal landing distance obtained from the aircraft performance database. If the runway is shorter than it is not considered as suitable for landing (suitability is 0). Point "b" defines a reasonable landing distance. This distance was introduced as expert knowledge and was defined as thrice minimum landing distance. It was done not to unnecessarily favor airports with long runways when searching for the emergency solution of small aircraft. Each runway suitability is 1 if its length is above reasonable landing distance.

In phase B distances to the airports are calculated using haversine formula which defines the shortest path possible. Route planning methods used in the next phase can only extend the trajectory to avoid obstacles, terrain hazards and weather

Figure 2 Membership function used for runway suitability definition



hazards. Knowing the estimated distance and speed, another estimation can be made. This time on the estimated time to the runways. Again membership function is used to define suitability. This time for all routes which are, by experts knowledge, of a distance greater than 30 min of flight away from current aircraft position suitability is equal to 0. Because at this point, estimation error can play a role in the decision-making process every runway that is less than 5 min away, is given a suitability score of 1.

Phase B is ended by applying a multiple-criteria decision-making method, where scores are given to each runway delivered from phase A. Runways are then sorted, and the finite number of once with the highest score is passed to next phase.

In phase C, paths to each runway are calculated and stored in the internal memory of the FRS. Tests conducted during the development of FRS showed that at this stage multiple well-known methods can be used such as A*, D*, Dubbins path method to calculate actual path, to deliver optimal path safe of hazards *en route*.

Information on routes lengths and complexities (measured by the number of waypoints *en route*) is then passed to phase D, where the MCDM method is used once again for scoring routes combined with runway scores, to choose the best route.

Main limitation of using complex MCDM methods were limitations given by possibility of hardware implementation. For this reason, weighted sum model was adopted as a method for MCDM used in phase B and phase D, which can be found in publication of Triantaphyllou (2000). It is simple in implementation, and suitable when limited resources are available to provide answers. The important part is that when using such a method mandatory criteria must be kept (minima for landing), prior to defining a score for the runway. In the case where for one of mandatory criterions weight of runway will be zero, such a runway must be disregarded as a potential landing place (overall score for the runway is also equal to zero).

When the emergency button is engaged, the route stored in memory is combined with information from onboard systems (such as GNSS receiver, AHRS, Air Data Computer) and autopilot commands are calculated. These commands are feed into autopilot to execute route.

Flight reconfiguration – system hardware

Dedicated equipment was created for the needs of the project. The FRS hardware has been designed as a separate, standalone, on-board electronic module – the element of the COAST Avionics System. This module was designated to complete a number of tasks briefly described below.

- to host the embedded FRS SW software file and to fulfill the requirement to execute this FRS SW file in real-time regime;
- to receive (via the FRS HW's sub-unit of the appropriate, well-defined interfaces) the data sets from adjacent units of aircraft's avionics (modules of the COAST Avionics, as well as other modules of avionic onboard equipment), which are required by the FRS SW;
- to deliver the appropriate data received from adjacent units to FRS SW module and transmit data produced by the FRS SW to adjacent units; and
- to carry out the data exchange operations (in/out) under requirements imposed by the FRS SW module and the FRS algorithm.

The laboratory model of FRS hardware was designed as especially susceptible to the implementation of modifications, even deep changes in the HW arrangement. The needs for such changes and modifications were expected to emerge during the process of FRS software synthesis and maturation of requirements imposed by the FRS software module. The beginning of the designing process of equipment was carried out simultaneously with the work on FRS algorithms. Finally, it was decided to create a hardware structure of maximum flexibility, regarding the possible changes and testing. Finally, the laboratory model comprises three boards. The first one, the power supply sub-module is dedicated strictly to electrical power management, delivers all electrical supplies. The second one, interface sub-module, contains all dedicated integrated circuits, necessary for data transfer (communication) between avionic modules (COAST modules and other) adjacent to the FRS HW module. The third one, the processor sub-module, contains the microcontroller and memory units. This structure allows easy replacement of main sub-modules when a need appears.

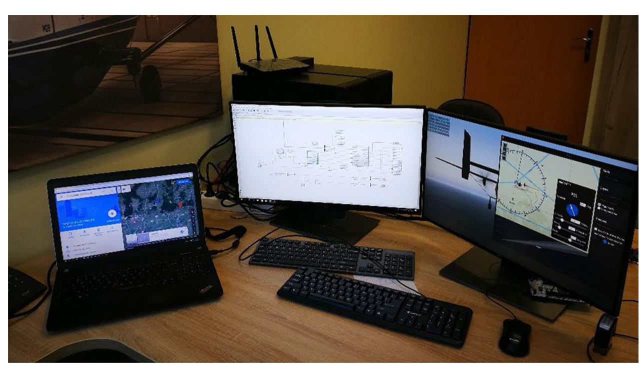
Verification process

The verification process was for the purpose of this paper divided into sub-sections related separately to FRS algorithms and FRS hardware. Tests of algorithms were conducted with the use of Software-In-The-Loop laboratory stand which was developed in Rzeszów University of Technology (Figure 3). Experience in the design of such stands was used to overcome the problem of integration of software model with the real-life simulation of the flight model (Kopecki *et al.*, 2016; Rzucidło *et al.*, 2013).

Algorithm verification – phase A

For verification of phase A, a test was created. A set of 13,341 runways worldwide was given in the initial database. By defining the aircraft position and comparing the distance to runway against a maximal range of aircraft it was predicted that the initial database can be reduced to less than 30% of the initial database. The worst-case scenario for such a test was considered to use for simulation was considering aircraft of

Figure 3 Software-In-The-Loop laboratory stand used for algorithm verification



range of above 1000 km in the middle of Europe. The actual test was made using data on M-28 – a commuter category aircraft, which range is approximately 1420 km. Its initial position for the purpose of the test was the vicinity of Frankfurt (50.244846 N, 8.533659 E). Figure 4 presents a visual representation of a number of airports in each sector of 1 × 1 deg of geographical position around the world (left side of the picture – briefly visible that highest number of airports is in North America and Europe) and reduced database (right side of the picture).

The database after applying of range criterion was consisting of 1,845 runways, so 13.72% of the initial database. Still, without applying the next phases, the number of runways to be considered can be a problem to deliver emergency solutions on time (especially calculating path to define distance needed for decision-making process).

Algorithm verification – phase B

The purpose of testing this phase was to compare FRS predicted runways given to phase C against the knowledge of human pilot experienced in the geography of the region for which test was performed. For the purpose of test, vicinity of Rzeszów has been assumed as the initial position of aircraft for route calculation and aircraft heading toward the Beskid Niski mountain range. Runway limit passed to phase C was defined as 20 runways, for giving the possibility of comparing against human. Figure 5 presents the results of the scoring and sorting process in phase B with the use of SAW method. Using criteria defined in paragraph 2 and with the use of MCDM methods, it was possible to reduce the database of over 1,300 airports to 20 most suitable airports which satisfy criteria for landing and distance. Almost all of the airports with the highest score are airports that were chosen prior to performing the test by an experienced pilot. Some were not indicated by him (like UKLU – Uzohhorod International Airport), as two possibilities may occur – lack of knowledge of experienced pilot on airports abroad EU or on purpose not indicating airports abroad EU. This motivation has to be further studied. Scoring of each airport is shown in Column 11.

Figure 4 Example of airport database reduction process in phase A

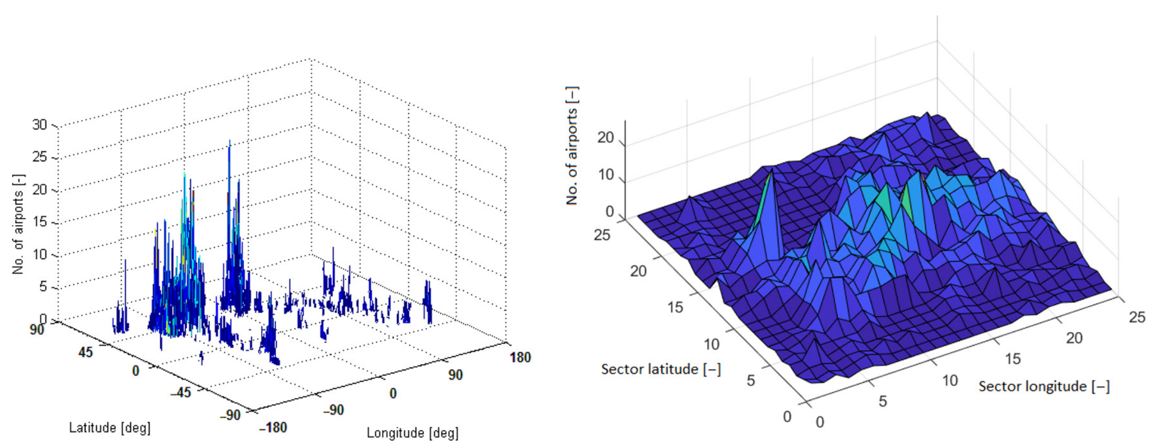


Figure 5 Example of runway scoring for phase B of the FRS algorithm

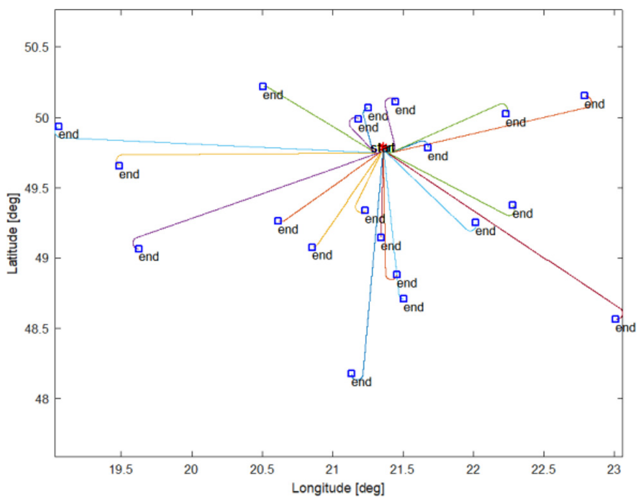
ICAO code	Runway length [m]	Runway direction [deg]	Longitude [deg]	Lattitude [deg]	ILS freq [MHz]	Runway direction [deg]	Runway altitude [m]	Runway distance [km]	Score <0,1>
EPRZ'	3.2001e+03	85	50.1102	22.0015	000.00	85	211.2264	57.9879	0.9977
EPRZ'	3.2001e+03	265	50.1096	22.0462	110.30	265	211.2264	60.4991	0.9935
LZTT'	2.5999e+03	269	49.0728	20.2589	110.10	269	718.1088	112.7833	0.9221
LZTT'	2.5999e+03	89	49.0744	20.2234	000.00	89	718.1088	114.4829	0.9193
EPKK'	2.5500e+03	253	50.0798	19.7997	110.30	253	241.0968	116.4072	0.9008
EPKK'	2.5500e+03	73	50.0754	19.7681	000.00	73	241.0968	118.4522	0.8974
LZKZ'	3.1001e+03	188	48.6766	21.2459	000.00	188	230.1240	124.0399	0.8877
LZKZ'	3.1001e+03	8	48.6494	21.2364	109.50	8	230.1240	127.1019	0.8825
EPNT'	1.6801e+03	298	49.4579	20.0620	000.00	298	627.8880	100.6671	0.8662
EPNT’	1.6801e+03	118	49.4659	20.0423	000.00	118	627.8880	101.6597	0.8645
UKLU'	2.0379e+03	98	48.6366	22.2497	000.00	98	117.0432	143.4936	0.8515
UKLU'	2.0379e+03	278	48.6336	22.2681	000.00	278	117.0432	144.3889	0.8500
LZSK'	1.2000e+03	9	49.3287	21.5682	000.00	9	353.8728	53.3542	0.8165
LZSK'	1.2000e+03	189	49.3375	21.5713	000.00	189	353.8728	52.4740	0.8165
EPKT'	3.2001e+03	265	50.4760	19.1001	109.90	265	306.9336	178.3880	0.7991
EPRA'	2.0001e+03	69	51.3870	21.2006	000.00	69	189.8904	177.9950	0.7960
EPRA'	2.0001e+03	249	51.3912	21.2255	000.00	249	189.8904	178.3531	0.7954
EPKT'	3.2001e+03	85	50.4761	19.0596	000.00	85	306.9336	181.0095	0.7947
UKIL'	3.3049e+03	130	49.8178	23.9463	109.50	130	328.2696	185.4550	0.7880
EPKR'	1.0750e+03	131	49.6831	21.7336	000.00	131	280.1112	29.1888	0.7879

Algorithm verification – phase C

The initial conditions for the test of phase C were the same as for tests in phase B. Expected output from Phase C of FRS SW should be routed database correlated with airports and in particular runways of each airport. For the purpose of test, Dubbin's path algorithm was used.

Figure 6 presents results of Dubbin's paths created during Phase C. Characteristic "hooks" at end of each line are correlated with procedural turn (3 deg/s) at a given speed, and they end at the approach point for airports delivered in Phase B of the algorithm with heading same as heading of the runway. Route lengths and the estimated time of arrival were also calculated during this phase. No collision with ground obstacles was noticed. Routes calculated by FRS were stored in separate files for each of them. It is still possible to encounter problems of route definition when flying on low altitude in the area with a big number of obstacles, and further investigations must be made for such cases. Different algorithms can be adapted to perform such tasks, yet also considerations must be made in terms of possible breaking the rules of air law.

Figure 6 Example results of routes definition using Dubbin's path method



Algorithm verification – phase D

The purpose of the test at this stage was to verify whether MCDM methods can be used for defining the best route. A similar method as for phase B was used, but distances to runways were changed, as better estimates of distance were delivered from phase C of the algorithm. Phase D should define emergency solution as the airport with the highest score. Airport defined by the FRS as the emergency solution (EPRZ Rzeszów Airport) was matching airport indicated by a human pilot. The next step was to verify if route stored in the form of a file (calculated in phase C) could be used to command autopilot. For this purpose, simulation model of aircraft with autopilot was used. FRS successfully converted information on waypoints stored in files containing routes to find cross-track and vertical deviation to each route leg. These signals were used to command autopilot which was simulated within Software-In-The-Loop simulation. The internal mechanism which calculated the distance to leg end waypoint allowed to switch waypoints automatically, when aircraft was in the vicinity of such a waypoint. This allowed executing route which consisted of multiple waypoints. Figure 7 shows a route that was executed by the simulation model of M28 aircraft in the vicinity of Rzeszów. Route execution lead aircraft to the final approach phase of EPRZ runway 27. The path of the aircraft after activation of the algorithm is marked with a red arrow.

Laboratory stand for testing of flight reconfiguration system hardware

The process of the hardware validation consists of several tests. First, tests, carried out on FRS HW LM module, had to prove that electronic elements, integrated circuits and sub-units defining the FRS HW LM module are working properly and smoothly, in line with the requirements and application notes

Figure 7 Example results of route execution by the FRS in Software-In-The-Loop laboratory stand

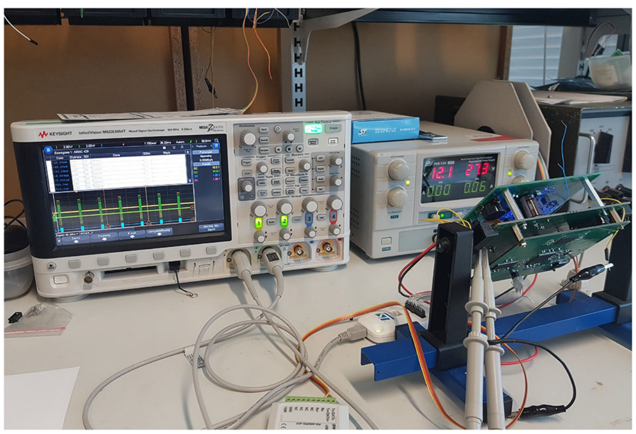
issued by its' manufacturers, as well as with assumptions of FRS HW LM design process and project expectations.

Additionally, tests proved that correct bilateral data exchange between the FRS HW LM module and PC laboratory computer has been established. Subsequent tests have shown that the FRS HW Board Support Package (BSP) software module is working properly and smoothly, according to the project expectations and assumptions of the design process. Moreover, it has been proved that the FRS HW LM module is capable to communicate correctly with the "outer world," i.e. the adjacent modules of COAST Avionics and with test aircraft onboard avionic system in line with required standards, protocols and assumptions defined in previous phases of the project. The laboratory stand configuration of the ARINC429 words is presented in Figure 8. The oscilloscope MSOX3054, presented in the figure, supports the decoding of the ARINC429 protocol. This type of data bus is used on most of the adjacent equipment of test aircraft on-board. Dedicated test software coded five empty messages sent in an infinite loop. The oscilloscope decoded those messages; hence, it has been proved that signal transmission is correct.

Figure 9 shows the proper decoding of the transmitted data. Further tests, carried out on FRS HW LM, were focused on the software integration. It has been proved that the FRS module is capable to communicate smoothly and efficiently with the FRS SW module, which is a kernel of FRS's SW. What is more, it has been proved that the FRS HW LM module is capable to carry on the process of FRS SW execution within the frame of the required timing.

Test showed that algorithms calculating FRS emergency solution can be successfully embedded into hardware and deliver the emergency solution in time less than 3 s, which makes it fast enough to use it in real-life situations.

Figure 8 Laboratory stand for FRS hardware tests



Conclusion

This paper presented briefly the development of tests conducted on FRS. It is one of the new branches of onboard systems that can autonomously define an emergency route for aircraft and execute it. Conducted tests showed that not only such a route can be delivered on time, and to be suitable according to criteria defined with the use of MCDM, but also algorithms providing it can be embedded into supporting hardware. It is worth noticing that the proposed that voting method for MCDM is very flexible on criteria given, and criteria for the definition of the final solution can be easily extended dependent on additional signals available onboard (e.g. if weather systems will give such as weather systems signals or traffic acknowledgments). Moreover, the path definition method can be changed dependent on system requirements. Many possible methods can be used efficiently starting from well-known, such as A*, D* or Djikstra algorithm, to less-used as based on airspace sectoring dedicated for free-route airspace. This is because the potential airport database is very limited compared to the initial one.

Figure 9 The signal of ARINC 429 transmission with its proper decoding on the oscilloscopes display

Further work

Inflight tests of FRS on commuter class aircraft are planned within the near future. As technology emerges detailed information about air traffic can be considered in the optimization process for delivering a new route, also information about weather and weather hazards. Such improvements will lead to extending the scope of navigational possibilities of FRS to the integrated mission management system (IMMS). Such a system would be used during regular flights to reduce overall CO_2 emission and flight time.

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