# Decision-making Algorithm in Case of Failure of the Electric Motor of a Multi-rotor Unmanned Aerial Vehicle

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**Abstract**

The safety of unmanned aerial vehicle (UAV) flights depends on many factors, such as the absence of failures or malfunctions of aviation equipment, the absence of exposure to adverse environmental phenomena, and the absence of errors by the aircraft crew and engineering personnel. In uncontrolled airspace by the internal affairs authorities, when the flight is carried out at altitudes below 500 feet above ground level (AGL), this task is even more complicated, since at the moment there are no monitoring services and procedures for monitoring VTOL-UAV (Vertical Take-Off and Landing unmanned aerial vehicle) performing operations at the specified altitude range. In this case, the only link of control is the remote pilot, who directly monitors his unmanned aerial vehicle (UAV) when flying in Visual Line-of-Sight (VLOS) mode. Some components of an unmanned vehicle are difficult to control from the point of view of preventing the risk of the likelihood of an incident, which is difficult to prevent due to its high potential danger and the speed of its occurrence.

In this paper, we propose an algorithm that is simple for software implementation and does not require mathematical calculations, the implementation of which requires the presence of devices for measuring the speed of rotation of engines, which are proposed to use Hall sensors installed on each engine of a multi-rotor VTOL-UAV.

To prevent the program from crashing when polling sensors, a double redundancy of sensor readings is provided. Also, in case of confirmation of an engine failure, a module has been introduced into the algorithm that provides for a preliminary shutdown of an engine that is symmetrical to the one whose failure is confirmed. After turning off the remaining engines, the parachute compartment is activated for an accurate landing at low speed.

**Keywords 1**

Algorithm, motor failure, aviation incident, VTOL-UAV

## 1. Introduction

The safety of unmanned aerial vehicle (UAV) flights depends on many factors, such as the absence of failures or malfunctions of aviation equipment, the absence of exposure to adverse environmental phenomena, and the absence of errors by the aircraft crew and engineering personnel. These factors are classified in the International Civil Aviation Organization (ICAO) risk matrix [1].

In controlled airspace, any manned aerial vehicle is under constant control of the crew and air traffic control units. The controllability of an unmanned aerial vehicle is a much more difficult task, since its crew- the remote pilot's team - are at a considerable distance and can assess the

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controllability of their aircraft based on telemetry data that comes along the downstream branch of the C2 channel.

In uncontrolled airspace by the internal affairs authorities, when the flight is carried out at altitudes below 500 feet above ground level (AGL), this task is even more complicated, since at the moment there are no monitoring services and procedures for monitoring VTOL-UAV (Vertical Take-Off and Landing unmanned aerial vehicle) performing operations at the specified altitude range. This altitude range is currently of particular interest to users, since it allows one to implement new or update existing high-tech production and economic processes. In this case, the only link of control is the remote pilot, who directly monitors his unmanned aerial vehicle (UAV) when flying in Visual Line-of-Sight (VLOS) mode, or based on telemetry data, with various Radio Line-of-Sight (RLOS) mode options. Some components of an unmanned vehicle are difficult to control from the point of view of preventing the risk of the likelihood of an incident, which is difficult to prevent due to its high potential danger and the speed of its occurrence. These components include the UAV electric motor. Failure of the UAV motor (sudden or partial) is referred to the group of aviation equipment failures.

## 2. Related works

In manned aviation, special attention is paid to assessing the risks of aircraft flight deviation from a given flight trajectory. To assess such risks, various methods are often used based on calculating the probability density function, while many publications on the topic of aviation risk assessment suggest a complex use of various options for calculating the probability density function. In particular, in [2], they propose to use a complex model called by the authors Triple Univariate Generalized Error Distribution (TUGED), which is supported by the Maximum Likelihood Method. The authors, by modeling, confirm the effectiveness of the proposed model by checking its compliance with the Chi-square, Bayesian and Akaike criteria.

In [3], it is indicated that the failure rate for various reasons for unmanned aircraft is 1/103 per flight hour, which is two orders of magnitude higher than the value of the same indicator for manned civil (commercial) aviation. Considering the above, the task of developing a decision-making algorithm in the event of a failure of the VTOL-UAV electric motor during flight is an urgent task to reduce the risk of an incident and, accordingly, increase the safety of VTOL-UAV flight.

According to [4], failures due to engine failure account for 411 cases per 1000 failures in general due to failures of various UAV components. It should be noted that this statistics took into account only the failures of internal combustion engines, which are now used on VTOL-UAV, performing long flights, more than one hour. In addition, the data takes into account the type of VTOL-UAV of the traditional aircraft type. In the same source, at the level of the components of the propulsion system, various failures are detailed - failures of the engine itself (63 cases), failures of the ignition system (97 cases); fuel system failures (120 cases), temperature control system failures (48 cases); failures of the management apparatus (83 cases).

As for the VTOL-UAV with an electric motor system, such statistics are either absent or not found. However, according to the experience of the authors, during experimental studies to determine the discharge rate of a LiON battery [5], brushless motors were used as a load, which are widely used as VTOL-UAV engines for vertical take-off and landing of VTOL and small HTOL (abbreviated as VTOL - Vertical Take-Off Landing [6]), weighing less than 25 kg. During the experiments, one of the engines suddenly failed for an unknown reason and was replaced with another. This case occurred under laboratory tests. It is obvious that under conditions of environmental changes during the flight, the probability of motor failure will increase.

In [7], a failure risk assessment was carried out for two VTOL-UAV designs: one VTOL-UAV design for vertical take-off and landing of VTOL (VTOL-UAV of this type is shown in Fig. 1) and another VTOL-UAV design for horizontal take-off and landing of HTOL (VTOL -UAV of this type is shown in Fig. 2, 3).

**Figure 1**: Multi-engine helicopter for cargo transportation PKM-14 "Saturn" [8]


**Figure 2**: Twin-engine unmanned aerial vehicle M-7V5 "Sky Patrol" [9]

**Figure 3**: Unmanned complex of hybrid type Zala Aero Zala Vtol

Zala Aero Zala Vtol is a hybrid unmanned complex, which, according to the developers, reduces the role of the human factor, the number of used and maintained equipment in the flight task, and fully automate flight processes. During operation, the equipment relies on the computing power of the on-board computer ZX1, which uses artificial intelligence technology, which allows to process data in Full HD and transmit HD video and photos via encrypted communication channels to NSU, ensuring effective monitoring before landing. . According to the developers, the versatility of the Zala Vtol design makes it fully compatible with all existing Zala target loads, and also allows the installation of additional surveying equipment.

According to preliminary calculations, the crash probability density (CPD) was calculated, which made it possible to determine the frontal impact area, which, in turn, was used to calculate the number of incidents (Expected Level of Safety) over a normalized time range using the Weibel and Hansman model of collision with the ground [10] (an incident in this model is understood as the number of impacts of an emergency board with a person, which leads to his injury or even death). Thus, for the push-type VTOL-UAV of horizontal take-off and landing with one diesel engine, $ELS_{HTOL}=1.47\cdot10^{-9}$ incidents/hour was obtained, and for the VTOL of vertical take-off and landing (quadrotor-in-quadrotor (QIQ) octocopter model) $ELS_{VTOL}=4,96\cdot10^{-8}$ incidents/hour. Whence it follows that the calculated incident rate for VTOL is almost an order of magnitude higher than for HTOL. The authors of [5] propose the calculation of the safety corridor when planning the flight trajectory, the width of which will depend on the obtained value of the accident probability density. For example, when a VTOL-UAV QIQ model is flying at an altitude of 122 m (400 ft) at a speed of 10 m/s, the width of such a corridor will be 38 m. In this case, the flight trajectory should not run through populated areas or crowded areas.

However, when used within dense urban areas with a high population density, it will be incredibly difficult to plan such a safe route, which will significantly complicate the implementation of the U-space concept.

The concept of constructing a trajectory based on the assessment of multiple risks in the U-space was also proposed in [11]. The authors proposed an extended structure of the UTM Risk Assessment Framework (URAF), which implies its use just for predicting the occurrence of the risk of an incident within the boundaries of a densely populated urban area from a multi-rotor VTOL-UAV. The onboard system, the hardware implementation of which is called the core Flight System, built on the Bayesian trust model, assumes, among other types of assessing the performance of various VTOL-UAV components, including monitoring the VTOL-UAV engine parameters. At the same time, the proposed flight risk assessment system, according to the authors, should be within the competence of the UAS Traffic Management (UTM) service, which, in fact, has not yet been created. Implementation of the proposed system would be an almost ideal solution to ensure security, but the declared implementation of the system in real time on board a specific VTOL-UAV, in our opinion, seems to be a difficult task, most likely not so much because of the large number of auxiliary hardware components, but also huge volumes of data that will only come from external sources. For example, data on the current population density in the flight area, or data on the strength of the protective coating (strength of the roof material). In addition, the authors did not take into account the very low degree of controllability of the multi-rotor VTOL-UAV in the event of a sudden failure of one of the engines. If such a failure occurs, the remote pilot will not be able to perform a touchdown operation at a new system-defined landing point or return to a departure point.

## 3. Problem statement

For unmanned aerial vehicles with vertical take-off and landing, there is no algorithm for ensuring the required safety during flight in the event of failure of one (or more) engines.

It is this type of VTOL-UAV that will be used for flights at very low level altitudes (VLL) and within dense urban areas (U-space). Since VTOL-UAV of this type is the most vulnerable to loss of control due to various failures, the development of decision-making algorithms in the event of failure of critical VTOL-UAV components, which include engines, is relevant, since it will help prevent an aviation incident.

## 4. Results

### 4.1. Expected risk of an incident due to motor failure

Consider how high the risk of an incident is in the event of a brushless motor failure. For technical devices, the most convenient reliability characteristics are failure rate and mean time between failures.

Failure rate - λ (t) is the conditional density of the uptime distribution for time t, provided that no failure of the device has occurred before time t.

$$\lambda(t) = \frac{a(t)}{P(t)}, \tag{1}$$

where $a(t)$ is failure rate, $P(t)$ is probability of failure-free operation. For practical purposes, the following statistical expression for the failure rate can be used

$$\lambda(t) = \frac{n(\Delta t)}{N_{av}\Delta t}, \tag{2}$$

where $n(\Delta t)$ is the number of devices that failed over time, $N_{av} = \frac{N_i + N_{i+1}}{2}$ is the average number of devices that work without failure over time $\Delta t$.

From [12] we know the boundary generalized values of the failure rate for small electrical machines, which include brushless motors - they are in the range from 0.01 to $8 \cdot 10^{-4}$ 1 / h.

The mean time between failures is defined as the mathematical expectation of the device operation until the first failure

$$MTBF = \frac{\sum_{i=1}^{N} t_i}{T}, \tag{3}$$

where $t_i$ is the uptime of the $i$-th device (until the first failure), h; $T$ is the total operating time of the device.

According to the same source, *MTBF* for small electrical machines is in the range of 1.000 to 20.000 hours. *MTBF* performance of high-quality brushless motors is the best among this group.

However, there are two factors, the influence of which, according to [12], significantly reduces the specified reliability characteristics. The first factor is the increased rotational speed expressed in rpm.

Thus, at a nominal rotation speed of 2500 rpm, the guaranteed uptime is 3000 hours, and when the speed rises to 9000 rpm (more than three times), the uptime is reduced to a value from 200 to 600 hours. That is, when the rotational speed is increased by three times, the failure-free operation is reduced by a factor of five or more! Therefore, taking this factor into account is mandatory when assessing the risk of an incident in the event of an engine failure.

The second factor that can significantly increase the likelihood of failure is the ambient temperature. Higher ambient temperatures also reduce guaranteed uptime. The dependences of the decrease in the uptime with a rise in temperature coincide significantly with the dependences under the influence of the factor of increased rotation speed. Thus, when assessing the risk of an incident, the temperature factor must also be taken into account. Moreover, the elimination of the influence of the first negative factor can be achieved by maintaining the nominal speed mode during manual remote piloting, or by introducing algorithmic restrictions when piloting in the autopilot mode. But the influence of the second factor, which is external to the unmanned aviation system, does not depend in any way on the remote pilot's command and thus must be taken into account when creating various algorithms for on-board systems that make it possible to increase the safety of VTOL-UAV flight.

## 4.2. Additional hardware tool to realization of developed algorithm

To implement the algorithm, it is necessary to have a device for monitoring the speed of rotation of the propeller, which is installed on the electric motor. As a similar device, one can use a speed sensor that operates on the basis of the magnetoelectric Hall effect. Some manufacturers of higher quality brushless motors already integrate Hall sensors into the motor design, which also serve as a positioning support. In this case, the task of providing motor control is simplified. But even if there are no sensors in the design of a brushless electric motor, it is possible to perform local design modifications by connecting an external sensor to each unit.


**Figure 4**: Hall sensor SS41F from SEC Electronic Inc. in 3-lead SIP package [13]

Such a sensor will record every change in the level of the magnetomotive force, which is induced due to the appearance of an electric current in the stator coils. Thus, information about the speed of each propeller from the Hall sensors will be transmitted to the VTOL-UAV microprocessor-based flight control system. To implement the algorithm, the number of sensors will be required, depending on the number of electric motors on the VTOL-UAV, since it is necessary to control the rotation speed of each electric motor using its own sensor. The main task of the developed algorithm is to monitor the performance of electric motors even in case of failure, which will be identified in the event of either no rotation or insufficient rotation speed of one of the motors. Since such a failure will immediately lead to a loss of control and the emergence of a conflict-hazardous situation, it is necessary to automatically work out a decision on the immediate termination of the VTOL-UAV mission and its landing.

The next device required for the implementation of the algorithm is a software module - a microprocessor or microcontroller. On board VTOL-UAV such a module is mandatory, and very often not alone - one microprocessor provides processing of navigation data from different navigation sensors, the second microprocessor is the core of the flight control system - autopilot. Since modern embedded microprocessors have a high degree of integration and contain several cores on their chip, both of these functions can be assigned to a single, high-performance microprocessor. However, many autopilot designers do separate navigation and control functions. Moreover, the latest trends in the development of on-board systems provide for equipping VTOL-UAV with microprocessors with a battery management system (BMS) [14, 15], which makes it possible to increase the level of VTOL-UAV flight safety. Since the microprocessor of the BMS system interacts with the electric motor, its software will require minor modifications by adding the code of the developed algorithm, which, due to the introduction of hardware controls, will be quite simple and compact in terms of the program code.

## 4.3. Design of the algorithm

With regard to the choice of the necessary hardware, the block diagram of the decision-making algorithm will have the following form, shown in Fig. 5. At the first step of the software implementation of the algorithm, it is necessary to set the failure counter - $x$ for the $i$-th engine. The counter of events (motor failures) can take the values of $x[i]=\{0, 1, 2\}$. The event counter is reset to zero during the initialization of the onboard control system before starting the flight. As a failure criterion, we will consider an event whereby the current value of the rotation speed of the $i$–th engine $V_{rot}[i]$ measured with the $i$-th sensor (*sensor* [$i$]) will be less than the required value of the speed $V_{reqrmnt}[i]$ or even equal to zero, necessary to ensure the controlled flight of VTOL-UAV. As long as the flight is in progress - the algorithm provides for a cyclic poll of the rotation sensors and compares the current measured speed value with the set value generated by the control system. In the case of the first fixation of a failure of one of $n$ electric motors, the counter of the $i$-th motor failure is incremented for the first time and takes the value $x\ [i] = 1$. After the initial setting of the failure counter, a re-confirmation check is performed, and if this check gives a negative result, the transition to the next step of the algorithm is performed. In this case, such an electric motor is considered to be conventionally failed, and information is sent to the control system about the repeated sending of a control action to this engine in order to establish the required value of its rotation speed. The control action is usually a PWM signal, the required pulse width of which is set by the processor of the VTOL-UAV control system.

If the condition $V_{rot}[i] < V_{reqrmnt}[i]$, is repeatedly satisfied, then the failure counter takes the value $x\ [i]=2$ and the transition to the algorithm branch responsible for the emergency termination of the flight occurs, since when one electric motor is inoperative, the probability of the origin of an aviation incident increases.

The emergency command block must contain two sequential procedures. In the event of a failure of one of the engines, the multi-rotor type VTOL-UAV immediately loses stability and begins to rotate around a horizontal or vertical axis. If at this moment in time all the engines are stopped at once and then the parachute compartment is opened for such an unstable VTOL-UAV, the parachute will get entangled around the hull and the VTOL-UAV will still make an uncontrolled fall, thus increasing the risk of an incident many times over.

In case of failure of one of the engines of the propeller-driven group, to stabilize the multi-rotor aircraft, it is necessary to immediately shut down the symmetrical engine, which is located diagonally opposite the suddenly failed engine according to the diagram shown in Fig. 6 where symmetric engines for a six-screw VTOL-UAV (hexacopter) are connected by a blue, red or green dashed line, respectively. After such a shutdown, the motors remaining in working condition will stabilize and prevent an uncontrolled fall for some time.

Thus, in the branch of the emergency subroutine, the emergency engine is first assigned a zero index - $j = 0$, then $x$ [0]. Following that, the symmetrical (diagonal) motor is turned off. The index of such an engine for a quadcopter will be $x[2]$, for a hexacopter $x[3]$, for an octacopter $x[4]$. To unify the algorithm in the block diagram of the algorithm, the symmetric motor index is denoted as *simmetr*.

After this operation, a short time delay of no more than 3 s is required to stabilize the aircraft. The block-diagram of the algorithm shows this delay as the *_delay* statement.

Further execution of the program involves sending a command to the flight control system to simultaneously turn off all other electric motors, which in a formalized form can be represented as a command $V_{rot}[i] = 0$, executed in a cycle. Next, the sending of the current coordinates is initiated, at which the flight is forcibly interrupted, via the downstream $C2$ subchannel to the remote pilot to notify him of the location of the VTOL-UAV, and a command is sent to the control system that initiates the opening of the parachute compartment and the release of the parachute. Then VTOL-UAV makes landing.

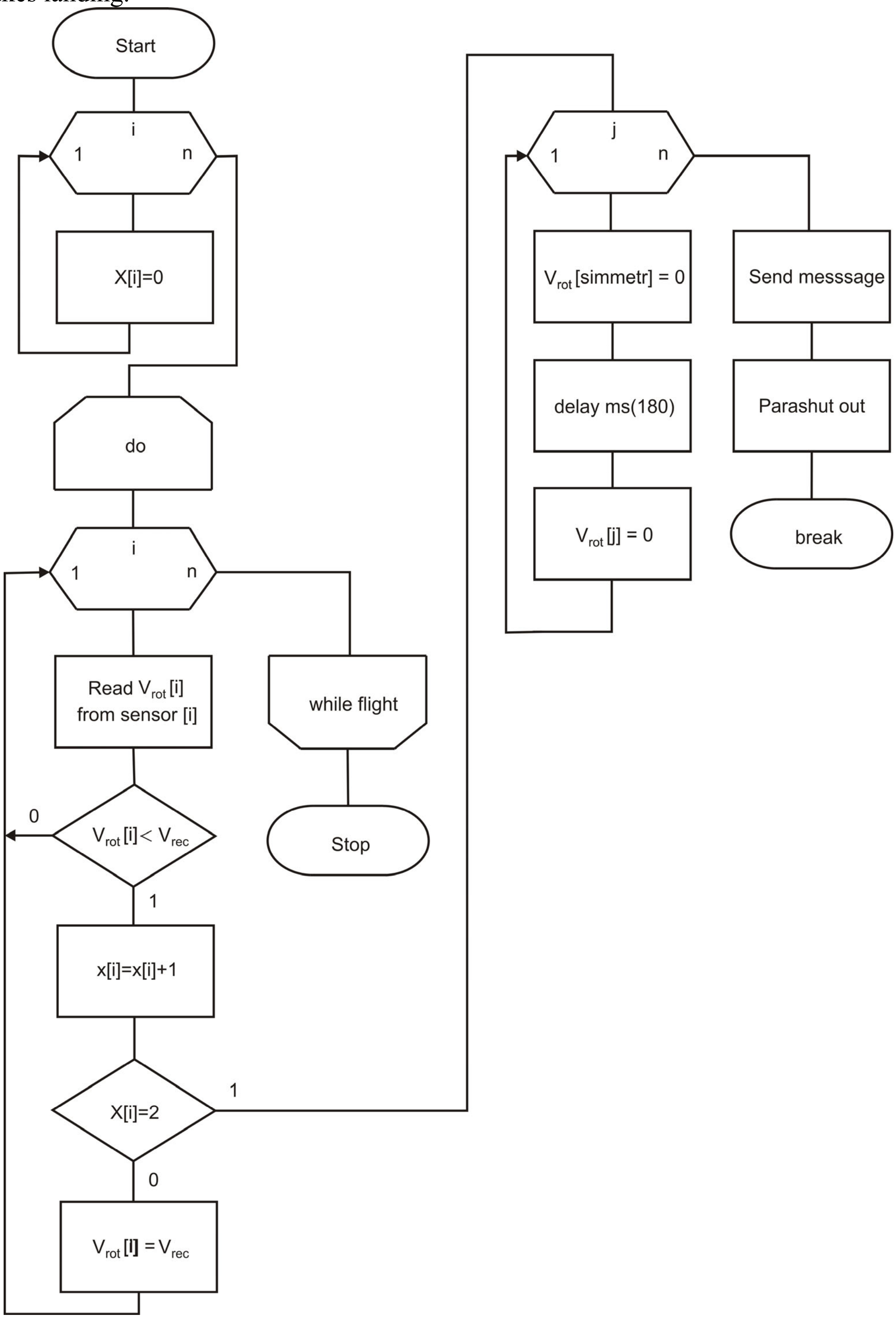


**Figure 5**: Block diagram of the decision-making algorithm in case of failure of the VTOL-UAV electric motor

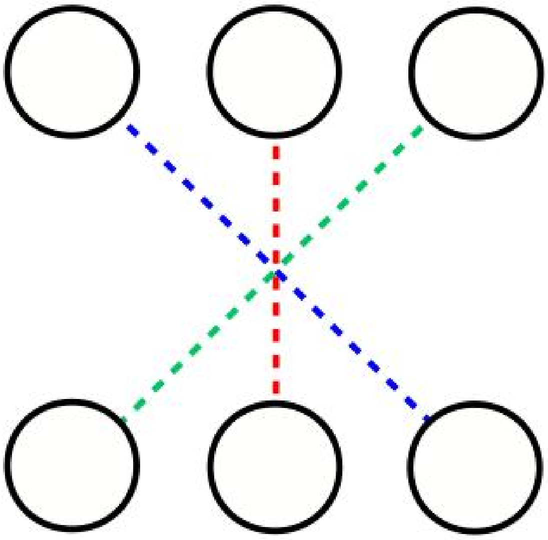

**Figure 6**: Diagram showing pairs of symmetrical motors for a hexacopter

## 5. Conclusions

Based on the analysis of sources, two negative factors have been identified that significantly reduce the standard indicators of the uptime of brushless motors and thus increase the risk of an incident: increased values of the speed of rotation of the rotor of the electric motor, which will be present in case of need for high-speed flight mode of VTOL-UAV and increased ambient temperature.

Taking into account the limited time for making a decision and preventing the risk of an incident, an algorithm that is simple for software implementation has been developed that does not require mathematical calculations, for the implementation of which it is necessary to have devices for measuring the speed of rotation of engines. For this purpose it is proposed to use Hall sensors installed on each engine of a multi-rotor VTOL-UAV.

To prevent the program from failure when polling sensors, double redundancy of sensor readings is provided. Also, in case of confirmation of engine failure, a module has been introduced into the algorithm providing for preliminary shutdown of the engine symmetrical to the one who has confirmed the failure. After turning off the rest of the engines, the parachute compartment is activated for an accurate landing at low speed.

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