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A Finite State Machine Based Adaptive Mission Control of Mini Aerial Vehicle

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Abstract[1]—This paper describes a finite state machine for adaptive mission control of mini aerial vehicles. The purpose of a finite state machine is to support mission control during aerial inspection of high voltage transmission lines and insulators independently from environmental and other conditions. One of the basic application of our mini aerial vehicle research is inspection of high voltage transmission lines during its load mode. Around high voltage transmission lines and towers generating a strong electromagnetic field. An electromagnetic field can be influence negatively to autonomous flight and mission control should be predicted such us situation to avoid possible accident.

Moreover, environmental and weather condition always unpredictable and mission control have to adapt for various type of additional constraints, which can be make problem for pre-defined mission map and trajectory.

Therefore, it needs to develop mission control for autonomous flight with an adaptive option or capability. Such mission control provides less workload and safety guarantee for the inspection team during the process.

Keywords—mini aerial vehicle; mission control; adaptation; finite state machine; autonomy;

I. Introduction

The Automated Power Line Inspection (APOLI) is the international project where cooperating universities of two countries (Germany and Mongolia) with industry to provide sustainable energy transmission in the country [1] [2]. This automated inspection system has limited capabilities depending on mission scenario. In contrast, adaptive mission control should adapt to all possible circumstances of power line inspection case and able to run the mission itself.

Before to discuss fully automatic systems, let us describe some key terms of this field.

A. Automation

Answering, "What is automation/autonomy?" and "How do we measure it?" or "What is our goal?" would be the first steps to develop an automated system. There are various definitions of automation and autonomy. For instance, "Automation can be defined as the technology by which a process or procedure is performed without human assistance" [3], and "Autonomy means that a robot can adapt to change in its environment or itself and continue to reach a goal" [4].

A number of researchers proposed different levels of autonomy to define Human-Robot Interaction (HRI) or automation/autonomy level of robots. First, in 1978, Sheridan and Verplank defined 10 levels of automation, based on human-robot tasks and information exchange [5]. In 1987, Endsley developed a 5-level automation classification in the context of the use of expert systems [6]. In 1999, Endsley and Kaber revised this approach and proposed a 10-level taxonomy [7]. Later in 2014, Beer, Fisk, and Rogers developed a 10-level taxonomy, which called Levels of robot Autonomy for HRI [8].

Based on above-referred research [7] [8] classification, and Sense-Think-Act paradigm [9], we developed a new taxonomy for adaptive mission control (see *Table 1*). There are five levels according to robot decision-making capability in our proposed metric:

1. Manual
2. Partly Automated
3. Shared Control
4. Semi-Automated
5. Full Autonomy

Table 1. MAV based Inspection System Autonomy Level

HRI ≈ 0%

Autonomy:	Level 1 *Manual*	Level 2 *Partly Automated*	Level 3 *Shared control*	Level 4 *Semi-Automated*	Level 5 *Full Autonomy*
Human role	• Mission planning • Sense environment • Make decision • Control the flight • Control the camera • Collect inspection data • Detect fault	• Mission planning • Sense environment • Make decision • Take control in emergency case • Control the camera • Collect inspection data • Detect fault	• Mission planning • Sense environment • Make decision • Take control in emergency case • Detect fault	• Mission planning • Sense environment • Take control in emergency case	• Mission planning
Sense *Sensor data Processing*		• Sensor data processing	• Sensor data processing • Image processing – Object detection	• Sensor data processing • Image processing – Object detection – Fault detection	• Sensor data processing • Image processing – Object detection – Fault detection • Sensor fusion
Think *Decision making*		• (Pre-defined plan)	• Mission Control v1 – Finite State Machine	• Mission Control v2 – Expert system	• Mission Control v3 – Advanced decision making system – Visual navigation
Act *Flight Control*	• Flight control	• Flight control	• Flight control • Camera control	• Flight control • Camera control	• Flight control • Camera control • Fault Report

Level by level decision-making solution gets more reliable, more intelligent, and more complex to run the Fully-Automated Mission. Higher level represents more autonomy and lower level represents less autonomy. The autonomy level comparison is shown in *Table 2*.

Proposed Autonomy Level in detail:

1. *Manual (Level 1)*

Here the human is the center of the process. The human performs all mission tasks. The system may or may not assist the human with simple functions for action.

2. *Partly Automated (Level 2)*

Human performs planning, sensing, and decision-making tasks. The system has limited sensing ability, able to perform a complex task according to a script or under human expert supervision. Here the human is still in the center of the process.

3. *Shared Control (Level 3)*

Human plan and monitor the mission procedure and able to take control. Both parties share sensing, decision-making tasks and the system performs action tasks fully. Center point of control is moved. The human is no more in the center of the process.

4. *Semi-Automated (Level 4)*

This is the pre-phase of the fully automated system. The human should plan and monitor the mission procedure and can to take control. The system automatically performs sensing, decision-making, and executing tasks.

5. *Full Autonomy (Level 5)*

The system performs all mission tasks: planning, sensing, decision-making, and acting. Although, system work automatically, the human is still involved in the mission by only starting it. The human is no more in the center of the process.

Our final goal is an Adaptive Mission Control (AMC) for (MAV) based inspection. Based on the proposed taxonomy, the current state of Mission Control is in Level 1 or Level 2, due to the predefined waypoint flight possibility which provided by the mission planning software.

Next step is the Level 3, where the operator plans and monitors the mission, and the system performs object detection (*Sense*), decision-making (*Think*) and controlling (*Act*) tasks during the mission. Object detection will be implemented based on computer vision techniques. Image processing part of AMC continuously feeds the decision-making part with desired data and parallel run a vision-based inspection. Flight and camera control tasks are executed by MAV flight control unit, under the control of human or robot decision. Decision-making is the essential part of AMC and this where we focused and proposed to use finite state machine (Section III).

Table 2. Autonomy level comparison

№	**Levels of Robot Autonomy for HRI** Fehler! Verweisquelle konnte nicht gefunden werden.	**Autonomy levels for APOLI**
1	Manual	Manual
2	Tele-operation	
3	Assisted Teleoperation	Partly Automated
4	Batch Processing	
5	Decision Support	
6	Shared Control With Human Initiative	Shared Control
7	Shared Control With Robot Initiative	
8	Executive Control	Semi-Automated
9	Supervisory Control	
10	Full Autonomy	Full Autonomy

B. Finite State Machine

FSMs are one of the most widely used models in computer programming in general. In particular, FSMs are ubiquitous in programming embedded systems and for describing digital circuits. A Finite State Machine (FSM) is a model of behavior using states and state transitions. A transition is a state change triggered by an input event, i.e. transitions map some state-event pairs to other states. As indicated in the name, the set of states should be finite. Also, it is assumed that there is a finite set of distinct input events or their categories (types, classes). Subsequently, the set of transitions is finite as well [10].

MAV flight has different states during flight, and it has to move from one state to another state. While MAV flying in automatic mode, state change has to depend on current input parameters and state. If we compare this picture with above standing definition of FSM, situations are similar and control of MAV can be solved by using FSMs.

The origin of FSMs is finite automata. A Finite Automaton is a more formal notion than a FSM. It is defined as a quintuple $(Q, \Sigma, q_0, F, \delta)$, where:

- Q - is a finite non-empty set of states
- Σ - is a finite non-empty set of input
- q_0 - is an initial state, an element of Q
- F - is a final state, an element of Q
- δ - is a transition functions

To provide MAV with AMC, some of our students worked on another solution for this using expert system [11].

II. ADAPTIVE MISSION CONTROL FOR MAV

Under the scope of the AMC development for various types of MAV based inspection application, we modeled a simple insulator inspection mission scenario. Fig.1 shows an abstract view of mission process.

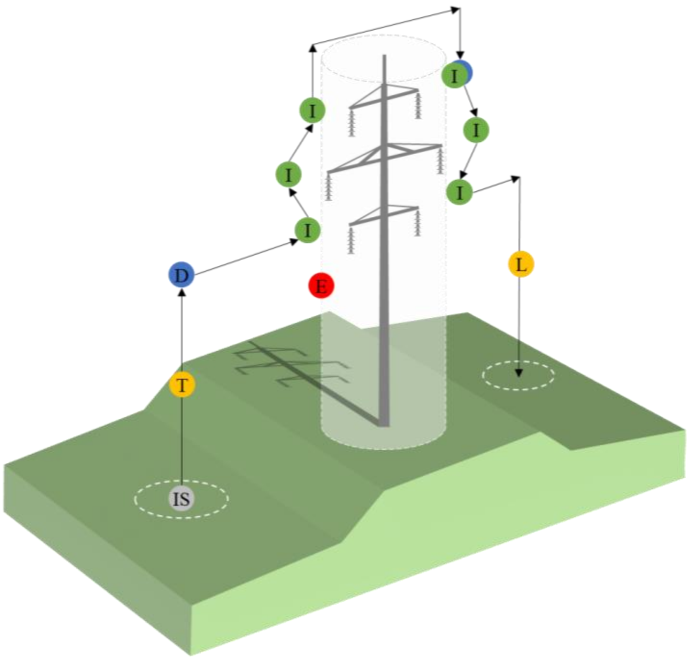

Fig. 1. States of insulator inspection process

Fig. 1 shows steps of an autonomous flight map. Each step becomes a state of FSM for the MAV mission control. There are several main tasks/actions (states) to fulfill the inspection completely:

1. Initial
2. Take off
3. Hold Position
4. Change Position
5. Search Object
6. Landing
7. Inspection
8. Emergency

Let us discuss every task in detail:

Initial

This is an initial stage of the mission, after the MAV turned on. The MAV has to be on the ground in distance of d (see Table 4) from power pole/tower main axis. During this state, operator and flight control computer do the connection, safety, and pre-arm check, and get ready the MAV for flight. According to mission and environment condition, there is no pre-defined time for this procedure.

Take Off

Pre-condition is that MAV should be on the ground and successfully initialized. The operator has to give start command to arm the MAV and start the *Take Off* task (or automated mission). The MAV will continue the taking off procedure until it reaches the given target height (h_{i1}). For h_{i1} see Table 3.

Table 3. Height parameters list for Automated Mission

Notation	Height (m)	Description
h_{i1}	13.5	Height of lower Insulator
h_{i2}	17.5	Height of middle Insulator
h_{i3}	21.5	Height of upper Insulator
h_t	24.5	Total height of tower/pole
h_r	8	Reserve height for pass over flight

Hold Position

This is an intermediate state of the flight, which is used between any position changing actions. Also, widely used for stabilize MAV condition or during the detailed inspection process. Due to the application, there could be pre-defined time for this procedure.

Change Position

Pre-condition is that MAV should be on the air and the previous task executed successfully. This is the main action of the flight and it has two main applications during the flight. The first one is for position changing. In simple position changing procedure, it is guided by certain h height or d horizontal position parameters (see Table 3 and Table 4). The second one is the inspection process. During the inspection process, the flight is guided by visual navigation and the inspection object has to be continuously detected.

Table 4. Distance parameters list for Automated Mission

Notation	Height (m)	Description
d_{st}	15,0	Starting distance from tower main axis
d_{i1}	4,0	Lower inspection distance from pole main axis
d_{i2}	5,5	Middle inspection distance from pole main axis
d_{i3}	4,0	Upper inspection distance from pole main axis
d_t	1,5	Additional distance for tower

d_{ep}	8,0	Safety distance of the pole (+4,0; -4,0)
d_{et}	12,0	Safety distance of the tower (+6,0; -6,0)
d_{po}	d_{i3}*2	Pass over distance

Search Object

The purpose of this action is to find the inspection object (insulator) with image processing algorithm [12]. MAV rotates in one position until it finds the inspection object. This is an initial action of the inspection process and crucial task of self-navigation. On the other hand, this is a transition face from GPS navigation to visual navigation.

Land

Pre-condition for this procedure is that MAV has to be on air and finished all mission tasks or in Emergency case. The main task of this state is to land the MAV safely.

There are three additional states in HVTL insulator inspection process. These are Flight, Inspection and Emergency actions.

Flight

This is a main flight state of the mission. All flight states are included in this state, except the Emergency state. The internal initial state is Take Off state and

Inspection

This is a main state of the inspection process. In this state, MAV flies according to the pre-defined path or under control of visual navigation to run the image-processing algorithm. Inspection state is a hierarchal state, which includes Hold Position, Change Position and History states. The transaction between Hold Position and Change Position state is depends on the mission task. In other words, this is the key state of each individual inspection missions for different tasks.

Emergency

In emergency cases, which are MAV misbehavior, entry to the restricted zone d_{ep}, d_{et} (Table 4), low voltage or other unsafe situations this state is triggered automatically or manually. Main goal is to prevent, avoid and eliminate the dangerous conditions. In Emergency state, MAV flight control switches to Position Hold Mode, so the operator can control the MAV manually. After the dangerous condition has been eliminated, the mission control arrives in the previous state.

III. STATE MACHINE FOR MISSION CONTROL

Based on the autonomy classification research and our taxonomy, we extracted subtasks for each level. For level 3 autonomy decision-making task, the FSM is proposed. The goal is to develop a sustainable and adaptable solution for this task. In case of insulator inspection and based on simplified mission scenario we developed a Mission Control FSM (*Fig. 2*) and a mathematic model of it.

- $Q = \{S_1, S_2, S_3, S_4, S_5, S_6, S_7\}$
- $\Sigma = \{I_1, I_2, I_3, I_4, I_5, I_6, I_7\}$
- $q_0 = S_1$
- $F = S_6$
- $\delta = Q \times \Sigma \rightarrow Q$ *(Table 5)*

According to *Fig. 2*, *Table 5* shows the transition function of FSM and all possible current and next states of MAV during the inspection process. By varying the distance or height (position) parameters, this generic FSM can execute different types of mission. The states are the following ones:

- S_1 – Initial;
- S_2 – Flight;
- S_3 – Take off;
- S_4 – Inspection;
- S_5 – Hold Position;
- S_6 – Change Position;
- S_7 – Search Object;
- S_8 – Land;
- S_9 – Emergency.

Mission control FSM is a hierarchical state machine and has total nine states. It starts from Initial state. The next main state is Flight state, which is triggered by a manual command and has refinement that consists of Take-off, Inspection, Land, Search Object, and History states. Inspection state is also super state, which has hierarchical Hold Position, Change Position and History states.

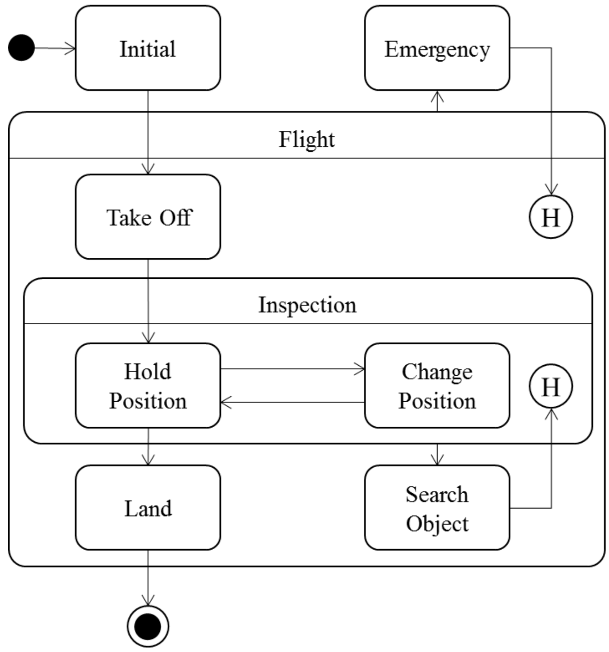

Fig. 2. Adaptive Mission Control FSM

For the state transition, there are six different inputs defined initially. These are:

- I_1 – whether the start button pressed (1) or not (0);
- I_2 – whether the target position reached (1) or not (0);
- I_3 – whether the target time reached (1) or not (0);
- I_4 – whether the inspection object detected (1) or not (0);
- I_5 – whether the inspection is done (1) or not (0);
- I_6 – whether the emergency condition occurred (1) or not (0).

According to the mission task, by modifying the Inspection state or varying the location values (Table 3 and Table 4) this generic FSM can execute different types of mission.

Table 5. Truth table of Adaptive Mission Control FSM

I_1	I_2	I_3	I_4	I_5	I_6	**Current State**	**Next State**
X	X	X	X	X	1	S_1	S_1
0	X	X	X	X	0	S_1	S_1
1	X	X	X	X	0	S_1	S_2
X	X	X	X	X	0	S_2	S_3
X	0	X	X	X	0	S_3	S_3
X	1	X	X	X	0	S_3	S_4
X	X	X	0	X	0	S_4	S_7
X	X	X	1	X	0	S_4	S_5
X	X	X	0	X	0	S_5	S_7
X	X	0	1	X	0	S_5	S_5
X	X	1	1	1	0	S_5	S_8
X	X	1	1	0	0	S_5	S_6
X	0	X	X	X	0	S_6	S_6
X	1	X	X	X	0	S_6	S_5
X	X	X	0	X	0	S_7	S_7
X	X	X	1	X	0	S_7	S_4(H)
X	0	X	X	X	0	S_8	S_8
X	1	X	X	X	0	S_8	S_1
X	X	X	X	X	0	S_9	S_2 (H)
X	X	X	X	X	1	$S_2 - S_9$	S_9

IV. Conclusion

The adaptive mission control of mini aerial vehicle base inspection system is an open question for researchers. The main objective is to reduce human role by increasing the technology solution in the inspection process. We proposed a 5-level autonomy taxonomy for HVTL insulator inspection case and subtracted the main tasks.

An FSM is one of the solutions to develop adaptive mission control of mini aerial vehicle base inspection system and here we discussed one version of FMS for adaptive mission control. An advantage of FMS is that it is easy to implement and test with the simulated scenario. A limitation is the lack of flexible, which would be needed for an adaptive mission control.

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