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Research Article

A Brief Overview of Autonomous Path Planning Algorithms for UAV Applications; reflections from a survey

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ABSTRACT

The past two decades of research on UAVs has revealed that about seventy percent of it had been published in the previous four years. To serve the exponentially increasing role of UAVs in multi-disciplinary research, the choice for most suitable path planning algorithms is presented in this work. The extent of autonomy in path planning for a UAV primarily depends upon the capabilities of its algorithm. Hence, a comprehensive survey study was proposed and conducted. This article presents a summary of the survey and suggests most suitable path planning algorithms for a UAV application. A collective consciousness was also developed while going through the process and presented on how the research work on intelligent robots should be categorized to cater future needs.

1. Introduction

UAVs can provide highly useful data, and their role becomes vital in information collection, aerial surveillance, industrial or agricultural monitoring, preventing disasters and so on. However, the most significant and common element among all would be accessing the real-time data and making autonomous decisions. The role of UAV systems, due to their cost effectiveness and ease of access to deploy has influentially motivated scientists to opt them as a tremendous support to research Nevertheless, this would require a higher level of autonomous behavior among UAVs.

An autonomous flight correctly points towards an onboard intelligent sensors-based system that is expected to set and modify the intermediate flight paths, to meet the mission objectives. An Unmanned Aerial Vehicle (UAV) may either follow a pre-programmed flight trajectory, a remotely operated path by a human or perform a dynamic path calculation during the flight [1]. At all the times in flight, a UAV must maintain or observe certain parameters and conditions for a stable flight, optimal energy consumption, fulfilling mission requirements and / or to restrain themselves within the areas of interest called boundary conditions. This gives a very significant role to the aspect of path planning in UAV operations, as a global objective, alongside the local dynamics of its requirements.

Usually, a UAV has a global and local set of dynamics and parameters alongside a high- and low-level control strategies, to be generic. Path planning is a matter of higher-level UAV control strategy where the UAV considers global parameters to reach it optimality conditions.

From a broader perspective, path planning can be categorized into two groups, namely offline and online path planning. The path planning before the take-off is offline while modification of flight path during the flight,

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as required by the mission objectives or the environmental dynamics, is online path planning.

The extent of maximum autonomy that a UAV can achieve is an arbitrarily undefinable goal because this primarily depends upon the degree of autonomous operations that a UAV may conduct. However, a certainty in this regard so far is that a higher level of autonomy would inevitably require the best exploitation of the onboard computational capabilities, where this phenomenon greatly relies on the abilities of onboard computational algorithms. Therefore, numerous approaches, criteria and innovations have been observed as significant efforts to enhance the performance of autonomous flights. The graph depicted in Fig.1. shows the published literature, indexed by the web of science, for the keyword "UAV" in the past 20 years. It shows that approximately 70% of the articles, published from 2016 to 2019 [2].

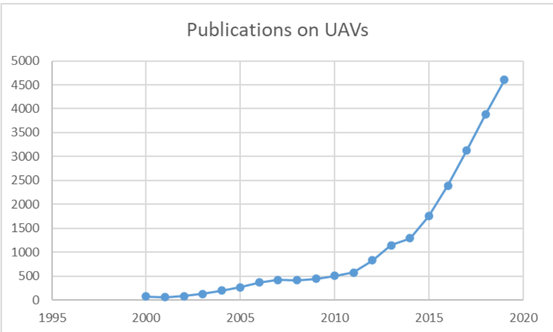

Fig. 1 Publications on UAVs in the past two decades

Another important factor to mention is the supporting role of UAVs in multidisciplinary research. This has contributed momentously in the spans of Geology, Chemistry, Environmental Sciences, Agriculture, Material Sciences, Physical Geography, Water Resources, Transportations, Mechanics, and many other research areas, elaborated in Fig.2 [7]. Optimistically, this has brought scientists and engineers much closer to several aspects of their research. As a matter of fact, this is because of the Unmanned Systems (UAVs, UGVs and UUVs) that have made collection of data much more cost effective as compared to the old traditional means of data acquisition.

Fig. 2 Contribution of UAVs in Multi-Disciplinary Research Areas (2000-2020)

2. Methodology

The selection of articles was based on two separate queries, *i.e.,* autonomous path planning for UAVs and autonomous UAVs swarm. The search was conducted on the *Web of Science Core Collection* database for the past five years. From the results, potential groups and subgroups were established. The research undertaken to improve the performance of existing algorithms or introducing innovative ideas for computing algorithms were grouped as developments in autonomous path planning algorithms. The rest of the part was considered as developments in UAV applications.

Algorithms were assigned labels relating to the category of their knowledge streams, as an instance, bio-inspired algorithms, graph search, *etc.* The algorithms in the second group were further labelled concerning the target application.

In section 6, anticipating the pace of developments in UAV's path planning algorithms, it is inferred that this technology is still somewhere in its evolution process.

After going through the literature survey and the thought processes, an overall collective consciousness is developed about the subsystems of any intelligent mobile robot or UAV.

This states that 'any substantial invention in one of the subsystems of a UAV, impacts the rest of its subsystems as well, in an order where the adjacent subsystem is affected the most.'

3. Needfulness

With exponential increase in the choice of path planning algorithms for UAVs, it was required to find the most suited set of path planning algorithm for a specific UAV application. After discovering the top-notch algorithms and applications, an application to algorithms mapping was presented to complete the picture. Some excellent surveys on path planning algorithms in recent years. In these surveys, the focus was relatively concise in most of them. A few studies about planning algorithms considered workspace dimensions [3], and obstacle avoidance [4], where the primarily concern was the nature of workspace and amount of information available to the robot. Another to mention is a technique-specific path computation [5], moving obstacles cluttered environments [6]. These dealt with the unexpected changes within the workspace and primarily deal with the lower-level control of the UAV. The considerations for this study were more towards practicality and direct in approach; first, the most recent developments in ongoing autonomous path planning applications and second, the algorithms associated with the most focused UAV applications. This helped to develop an application to algorithms mapping out of the recent published literature. that offers the reader with appropriate choices of algorithms for a specific UAV application.

4. Survey Findings

The conducted survey was categorized under two sections; one, most widely utilized algorithms and two, most significant UAV applications. The relation established between these two categories was found helpful in identifying the usefulness of algorithms and promising UAV applications. Hence, identifying the focus of UAV's path planning research and its directions. At here, only the survey findings from the algorithmic developments and most focused applications have been presented, respectively below.

It was found that the fusion of two or more algorithms was 25% of all the algorithms, and Evolutionary algorithms were widely chosen for the optimization process. However, the utilization of bio-inspired algorithms and modifications, if combined, these comprised 37% of the whole pie chart, depicted in Fig. 3.

From the survey, it was also observed that Cooperative Mission planning among UAVs has been the hottest and most focused research area in Autonomous Path Planning. Their reasons mainly include cost-effective, precision to conduct lower atmospheric aerial operations, ease of deployment, mobility, and accessibility of the required equipment. The second most attractive application was Sense & Avoid, followed by extended flight duration and coverage area, applications. New challenges have emerged in UAV research for communication infrastructure among UAVs, a unified identification of foes and friendly flights, secure communications, and UAV traffic regulatory systems.

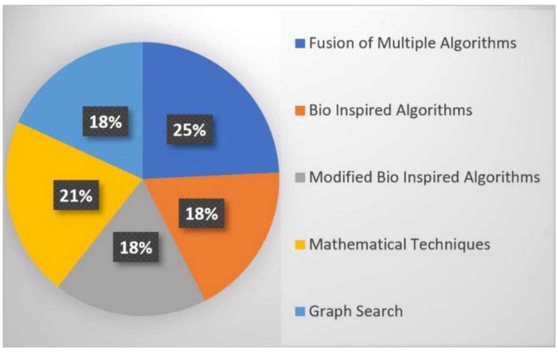

Fig.3. Breakdown of autonomous UAV path planning algorithms (left).and applications (right)

5. Survey Reflections

Very high diversity in path planning applications and available algorithms engendered skepticism about the selection of a better or most suited algorithm for a specific UAV application. Therefore, autonomous path planning applications and the algorithms utilized for these have been mapped in Fig. 5. However, there have been some worth mentioning observations:

1. It is quite disturbing to notice an absence of Machine Learning techniques

2. there can be observed a huge dominance of optimization algorithms.

3. The highest level of autonomy has not reached, and it stands as a goal not clear yet.

4. Any machine that is supposed to be intelligent must contain a set of specific smart or intelligent actions. The intelligent actions come from intelligent algorithms.

5. A criterion that can be foreseen at this point in time can be as follows: The selection of autonomous UAV's behavior from UAV itself, based on the randomness of its environment and mission objectives, ought to be rated as the highest degree of autonomy and hence may serve as the ultimate test of UAV's autonomy.

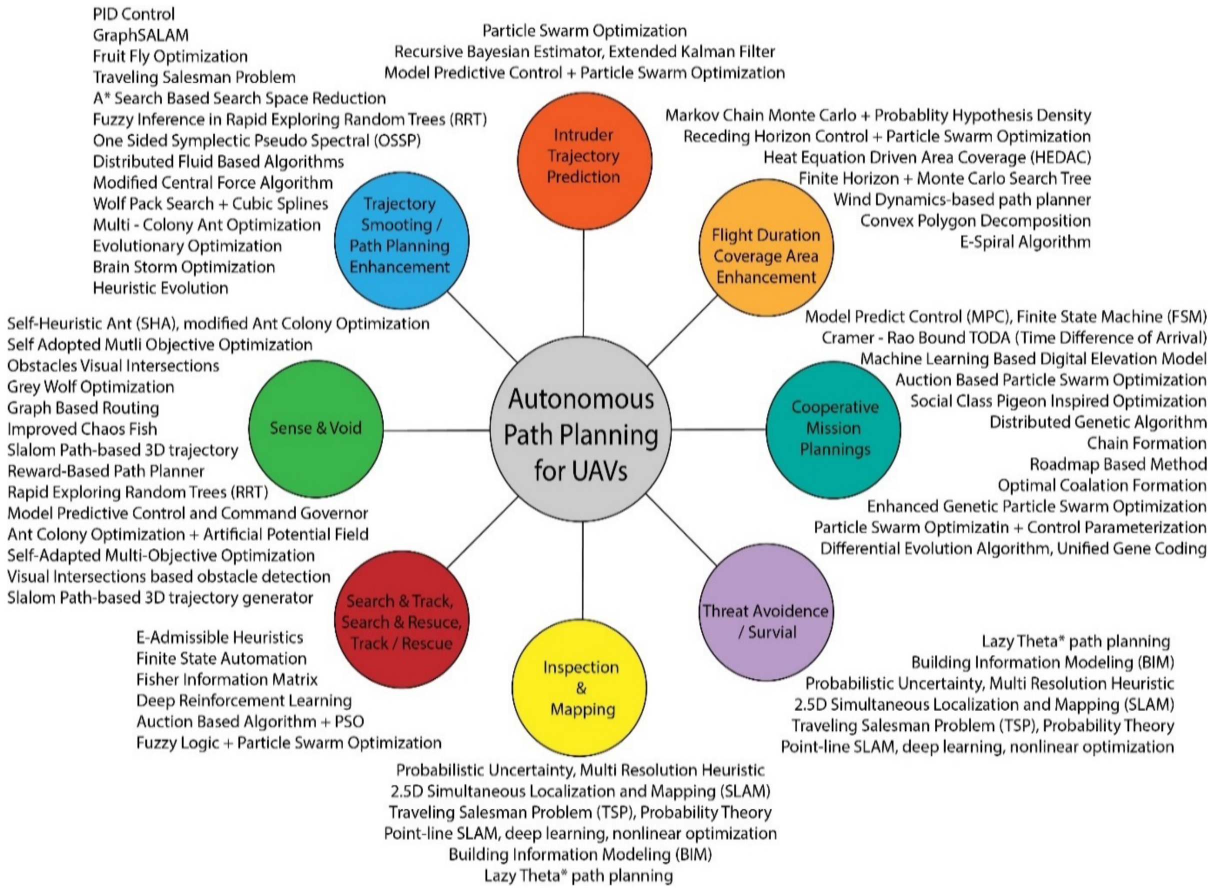

Fig. 4. Applications to Algorithms Mapping for Autonomous Path Planning of UAVs

6. Autonomous UAVs (Robots) through the Five Layers model

Considering the developments in Autonomous Path Planning of UAVs shown in Fig. 4 and an arbitrarily higher demand for autonomy from futuristic UAV applications, the progress of research & development (R&D) can be better examined if observed through a modular approach.

If the whole system is broken down into layers of five generic subsystems, it becomes convincingly obvious to perceive the role of each layer in UAV's flight and behavior. Hence, the bottlenecks in UAV's developments can also be identified through this approach, refer to Fig. 5.

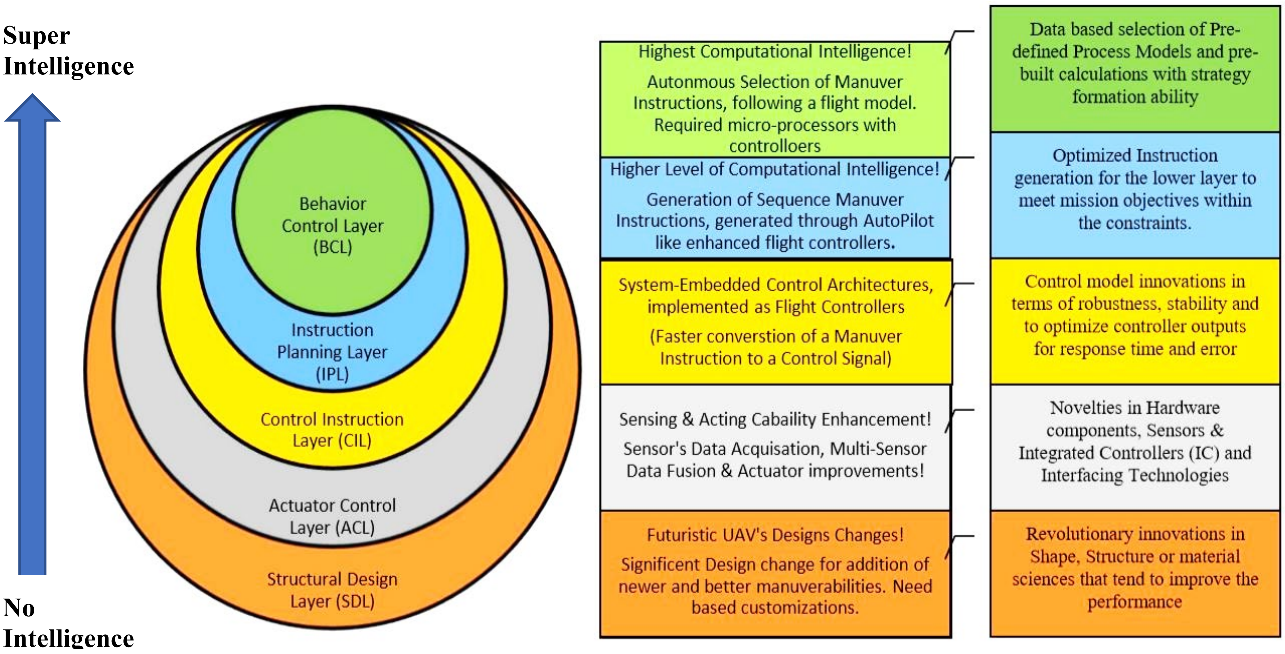

Fig. 5. Five Layers Breakdown of an Autonomous UAV (Robot) System

The breakdown should be viewed from top to bottom, considering the Structural Design Layer (SDL) as the most fundamental or basic subsystem, and the rest of the subsystems are built as layers above, sequentially. The impact of any up-gradation or degradation at one layer would be the most at the layers adjacent to it. For example, any modification in the Structural Design layer would best serve the Actuator Control Layer and least for Behavior Control Layer, the topmost layer.

Functionalities for each layer is presented below and it is proposed here that any research work related to intelligent robotics may be categorized through the following five layers model.

5.1 Structural Design Layer (DGL)

This layer considers the improvements and innovations in the structural modeling, aerodynamics, and manufacturing materials of the UAV. It is interesting to know that a simple application can impact the structural design as well.

Considering an example of a UAV that must collect specific atmospheric pollutant contents, the position of the sensor should remain, ineffective of the thrust from its propellers. These kinds of applications may be expected to imply a change in structural design. Consequently, the changes in the structural design may affect the component selection, its type, and effectiveness for a drone model.

The UAVs are expected to go through revolutionary structural changes either in the form of their shapes, fabrication material, or any coating technology. Miniature designs of UAVs are expected to be seen in action, backed by the Nanotechnology development platforms and IOTs.

5.2 Actuator Control Layer (ACL)

This layer serves as an interface to UAV’s environment and itself, mainly including the sensory components, interfacing technology, and actuator subsystems. Significant developments in the sensor’s technology, efficient actuators, or their combination would preside this layer. Researchers want to improve the aspects like energy consumptions at the hardware level, sensor data's voltage representations, and faster bus communications. The role of sensing technology may play a decisive role in the arrangements of UAV designs and its applications, for example, detecting colorless or odorless fluids can substantially affect the sensor interfaces and their fusion algorithms.

5.3 Control Instruction Layer (CIL)

The generation of control signals and commands to keep the UAVs operational and stable is the responsibility of this layer. It can either convert the instructions, received from the layer above, into control signals, or can directly generate the control instructions. Nowadays, there are commercially available UAVs with one-touch acrobatic maneuvers that are pre-programmed, are executed at this layer.

The concepts of high-speed racing drones have been realized due to highly efficient control models at this layer. A lower level of autonomous behavior like obstacle avoidance, LiDAR-based mapping, swiftly moving through a cluttered environment, and similar can be observed through an efficient CIL layer.

Supposedly, if the maximum ability of UAV is to follow a simple radio-controlled instruction, then this layer would suffice the need. The layers above this would not be required, and hence it can be inferred that a basic UAV system can be developed only with the three layers discussed so far.

5.4 Instruction Planning Layer (IPL)

The layer at which a UAV gets the ability to preprocess the control instructions from the maneuver instructions. It is responsible for resulting in a higher-level of autonomous behavior as compared to CIL. The layered is governed by the algorithms that generate autonomous instructions exploiting the hardware resources. The layer generates a sequence of instructions to meet the mission conditions and optimization constraints. Primarily, the sequence of instructions is generated because of some optimization or a path planning algorithm. The generated sequence of instructions is translated down to the Control Instruction Layer for execution.

The functionality of IPL is of utmost importance, and remarkably convenient by the availability of path planning software, offering a communicating channel with the UAV hardware, and embedded with built-in optimization algorithms to improve the process. Most of the work done so far, as observed in the survey, computes the instructions at this layer.

5.5 Behavior Control Layer (BCL)

On top of the IPL is the Behavior Control Layer (BCL) that involves the highest level of computational intelligence. Machine learning techniques based on autonomous systems to control the drone flight would preside this layer. Although, some of the works observed in the survey utilized machine learning techniques, however, on a fundamental level.

This layer offers a UAV the ability to exhibit the behavior of autonomous choice selection. Usually, the mechanism is based upon some pre-processed data sets and a prebuilt model to fit the data from the dynamic changes in the environment. At run time, the data collected from the sensors is processed to generate and match the pre-trained model. Such decisions mainly involve either estimation or prediction. From these estimations, the drone attains the ability to decide among a specific set of possible instructions to choose the finest ones for its mission objectives. The selected instruction is immediately passed on down-to the optimization level, where the sequence of execution is planned and further transferred to the control layer. Any algorithm that develops this computational capacity in the UAV is categorized at the Behavior Control Layer.

6. Discussion

The whole picture should be view in the context of the next proposed and immediate higher, functionality-specific level of Artificial Intelligence (AI) that is Artificial General Intelligence (AGI). At this stage, the most foreseen possible vision of any intelligent UAV can be imagined as:

‘The one being responsible of choosing a set of pre-evaluated strategies (or a series of actions) autonomously, trained over several independent environment-robot models where the intelligent actions would come from the algorithms governing them.’

Considering the 5-layer model, the role of computational intelligence or AI so far, primarily resides at the IPL because, in most of the cases, the UAV generates a trajectory based on an existing model, runtime data or conditions to exhibit an autonomous behavior. Whereas the promises of a futuristic intelligence capability would reside on the BCL. The survey found that the major focus of development resided at most within the IPL and not the BCL. Hence, linking back to the fact that the maximum level of autonomy of UAV still stands as a goal unclear.

However, the core of exhibiting revolutionary intelligence under many AGI behaviors would expect 'autonomous experience selection' from any robot or a UAV and this stands as an open challenge at the Behavior Control Layer (BCL). The UAVs at BCL would be required to devise a set of strategies i.e., distinguish set of actions in series, that are based on distinguish learnt experiences for unforeseen environments, yet known conditions. Hence, the future of super-intelligent UAVs resides at the BCL while the state of the art still waits for an integration of AGI with UAVs or mobile robots.

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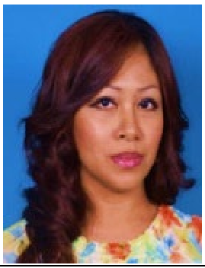

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