Expert Systems With Applications 70 (2017) 103–118

Contents lists available at ScienceDirect

Expert Systems With Applications

journal homepage: www.elsevier.com/locate/eswa

Analysing temporal performance profiles of UAV operators using time series clustering

Víctor Rodríguez-Fernández[a,*], Héctor D. Menéndez[b], David Camacho[a]

[a] Universidad Autónoma de Madrid (UAM) 28049, Madrid, Spain
[b] University College London (UCL), London, UK

ARTICLE INFO

Article history:
Received 27 July 2016
Revised 27 September 2016
Accepted 18 October 2016
Available online 28 October 2016

Keywords:
UAVs
UAV operators
Time Series Clustering
Performance measures
Simulation-Based Training

ABSTRACT

The continuing growth in the use of Unmanned Aerial Vehicles (UAVs) is causing an important social step forward in the performance of many sensitive tasks, reducing both human and economical risks. The work of UAV operators is a key aspect to guarantee the success of this kind of tasks, and thus UAV operations are studied in many research fields, ranging from human factors to data analysis and machine learning. The present work aims to describe the behaviour of operators over time using a profile-based model where the evolution of the operator performance during a mission is the main unit of measure. In order to compare how different operators act throughout a mission, we describe a methodology based of multivariate-time series clustering to define and analyse a set of representative temporal performance profiles. The proposed methodology is applied in a multi-UAV simulation environment with inexperienced operators, obtaining a fair description of the temporal behavioural patterns followed during the course of the simulation.

1. Introduction

Unmanned Aerial Vehicles (UAVs) have become a relevant area in the last decade. The main goal of this field is to replace human supervision in several sensitive tasks using UAVs in an accurate way. The automation of these tasks supposes an important step forward in several areas of our societies such as: agriculture, traffic, infrastructure inspection and forestry among others (Pereira et al., 2009).

In the current state of UAV research and development, there are some processes that can be almost totally automated with low risk, but others still require the role of the operator as a critical part of the entire system. A hard training of these operators is usually performed to guarantee that they have the appropriate attitudes to handle with this technology, specially in risky situations. The training process can also help to describe different features of the trainee, not only technical but also psychological aspects that might help to prevent dangerous circumstances.

This study focuses on UAV operators and takes information about how they evolve during a specific simulation, paying special attention to how their performance change during the process. With this information, we build a temporal performance profile of a simulation which will help to describe the decision abilities.

In previous works we were focused on describing a general profile of the operators, based on their behaviour during the whole simulation (Rodríguez-Fernández, Menéndez, & Camacho, 2015b). Also, the temporal interaction patterns during a mission were modelled through the use of Hidden Markov Models in Rodríguez-Fernández, Gonzalez-Pardo, and Camacho (2015). However, one of the most relevant aspects of the training process is the performance evolution during the simulation course. This work is focused on that attitude, creating temporal performance profiles for different simulations and then extracting and analysing the most representative of all.

In order to achieve the purposes of this work, we combined clustering techniques with time series analysis (Liao, 2005), to define a set of representative simulation profiles, based on the evolution of a set performance measures that describe the attitude of the operator in specific moments of a simulation. To test the validity of the proposed methodology, an experiment with inexperienced operators is carried out, simulating a training mission in a lightweight multi-UAV simulation environment, developed as part of our previous work in the field (Rodriguez-Fernandez, Menendez, & Camacho, 2015a). Several experiments have been carried out to evaluate the quality of the results of the methodology and to compare those results against other clustering approaches. Further-

* Corresponding author.
E-mail addresses: victor.rodriguez@inv.uam.es (V. Rodríguez-Fernández), h.menendez@ucl.ac.uk (H.D. Menéndez), david.camacho@uam.es (D. Camacho).

http://dx.doi.org/10.1016/j.eswa.2016.10.044

more, a qualitative analysis of the results have been made in the context of the experimental simulation environment.

In sum, this paper presents the following contributions:

- A new multi-variate time series clustering methodology is defined in the context of performance analysis for UAV operations. The proposed methodology is divided into two steps: the first focused on finding patterns in each dimension of the multivariate time series and the second focused on generating a multivariate distance using the patterns found in the previous step.
- The proposed methodology is scalable to the use of different time series dissimilarity metrics, different clustering methods and different number of clusters.
- A collective human judgement-based evaluation process is carried out to create ground truth information with which we are able to evaluate and compare the results of the proposed methodology.
- A quantitative and qualitative interpretation is given for the results obtained in a lightweight multi-UAV simulation environment.

The rest of the paper is structured as follows: next section presents the Related Work, after, Section 3 describes the proposed methodology, emphasizing on its division into two steps. Then, Section 4 provides a description of how to apply the proposed methodology to a specific simulation environment, detailing the environment itself, the defined performance measures comprising a simulation profile, and the evaluation criteria used to judge whether the results are right in an objective way. In Section 5 we carry out some experiments to evaluate and compare quantitatively the quality of the proposed methodology, and afterwards, Section 6 makes a qualitative analysis of the results obtained. Finally, Section 7 presents the conclusions and future work.

2. Related work

This section aims to provide a general overview around the two main fields of this work: UAV's research and machine learning algorithms. We start by introducing the current problems that have been frequently studied in UAVs and after that, we describe clustering models that can be found in the literature.

2.1. UAVs research

UAVs research aims to solve different problems related to this area in order to create a competitive field that can help in societies development, by automating complex human tasks. Several of the ideas are based on the design and development of these new vehicles, however, from this work perspective, we are more aware about the intelligence and the autonomy of these systems, specially for the new multi-UAVs systems.

Since the current state of the research do not allow fully independent and intelligent UAV operations, it is important to focus on the human factors associated to these technologies. Considering the importance of the operator work and, specially, the sensitiveness of their tasks and the costs of these technologies from both human and economical perspectives. It is critical to have appropriate means to measure and monitor the operator performance. For this reason, there are several works focused on analysing behavioural features during UAV operations, specially in the fields of Human Supervisory Control (HSC) and Human-Robot Interaction (HRI) systems (McCarley & Wickens, 2004). These features are usually measured according to the performance standards on HRI systems, which focus on the operator workload and its *Situational Awareness* (Drury, Scholtz, & Yanco, 2003). In order to gather information related to direct measures of performance, as the ones used in this work, some ideas are taken from the video games field (Begis, 2000).

From a more general perspective, there are two main research lines in Unmanned Aircraft System (UAS) systems: those focused on the system design (Lemaire, Alami, & Lacroix, 2004) and those developing efficient training processes for the operators (McCarley & Wickens, 2004). The former is relevant according to the number of operators needed to manage a single UAV (typically the model is many-to-one, where several operators manage a single UAV). The later, related to the former, is focused on how to prepare the new operators to deal with these complex tasks, ensuring that the trainee is highly qualified after this process. Due to these systems are currently evolving fast, the training systems need to be redesigned frequently, in order to meet the demands. Besides, in order to cope with the enormous future demand of UAVs operators, it is interesting to extend the availability of these technologies to new inexperienced but promising users, such as video game players (McKinley, McIntire, & Funke, 2011).

2.2. Machine Learning and Clustering Analysis

Machine Learning is the process of extracting knowledge-based models from data, identifying different patterns (Larose, 2005). Machine Learning techniques have been successfully applied to several different fields, such as *medicine* (Lavrač, 1999), *sports* (Menéndez, Bello-Orgaz, & Camacho, 2013), *security* (Portnoy, Eskin, & Stolfo, 2001) and *transport* (Liao, Patterson, Fox, & Kautz, 2007), among others. There are several areas related to Machine Learning, however, in this work we focus on unsupervised learning, specifically clustering analysis (Larose, 2005).

Clustering is focused on discovering knowledge blindly with no labelled information (Larose, 2005). This process groups the data according to some criteria defined by the analyser. The groups are named clusters and satisfies two main properties: the objects inside a cluster are related to each other, and objects of different clusters are different (Hruschka, Campello, Freitas, & de Carvalho, 2009). These properties make the evaluation process a difficult task (Schaeffer, 2007), and it is still an open problem. However, there are some validation methods based on evaluation indexes (such as the Silhouette or the Dunn index) that provide an objective quality measure of the clustering discrimination process. There are lots of clustering algorithms, some of them based on different perspectives of the clustering problem and the information that can be extracted from the search space. Good and relevant examples are the centroid-based approaches (Macqueen, 1967), where the algorithm optimizes the position of a set of centroids in a known search space, and medoid-based approaches (Kaufman & Rousseeuw, 1987), where the features of the search space are unknown and only the distance between the data instances is known. Using this distance, the most relevant data instances (the so-called medoids) are chosen as the most representative elements of each cluster.

The most classical clustering algorithms are K-means (Macqueen, 1967), Expectation Maximization (Dempster, Laird, & Rubin, 1977) and Hierarchical Clustering. The first two algorithms are based on statistical iterations over the parameters of a specific estimator, while Hierarchical Clustering nests the clusters by hierarchical levels, describing degrees of similarity by level. Modern algorithms are based on other properties that can be extracted from data, such as continuity (von Luxburg, 2007) (i.e., the shape defined by the data in the space) or density (Navarro, Frenk, & White, 1997). These different ways of dividing the space increase the analyst choices when selecting the appropriate algorithm, and thus the validation process becomes a relevant step in order to determine which is the best solution for a given dataset with respect to the algorithm and metric. Furthermore, another