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A cloned linguistic decision tree controller for real-time path planning in hostile environments ☆

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Abstract

The idea of a Cloned Controller to approximate optimised control algorithms in a real-time environment is introduced. A Cloned Controller is demonstrated using Linguistic Decision Trees (LDTs) to clone a Model Predictive Controller (MPC) based on Mixed Integer Linear Programming (MILP) for Unmanned Aerial Vehicle (UAV) path planning through a hostile environment. Modifications to the LDT algorithm are proposed to account for attributes with circular domains, such as bearings, and discontinuous output functions. The cloned controller is shown to produce near optimal paths whilst significantly reducing the decision period. Further investigation shows that the cloned controller generalises to the multi-obstacle case although this can lead to situations far outside of the training dataset and consequently result in decisions with a high level of uncertainty. A modification to the algorithm to improve the performance in regions of high uncertainty is proposed and shown to further enhance generalisation. The resulting controller combines the high performance of MPC–MILP with the rapid response of an LDT while providing a degree of transparency/interpretability of the decision making.

Keywords: Learning; Fuzzy control; Linguistic modelling; Optimization; Behavioural cloning; Interpretability; UAV

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1. Introduction

Behavioural cloning [1–3] has been used to imitate human control of systems that are difficult to model analytically. A limitation of such approaches is clearly that the clone can only be as good as the human it is imitating. An alternative application is in complex real-time systems where the control policy must be determined very rapidly, whilst it may be possible to model such systems, deriving the control policy in real-time is often challenging such as the control of obstacle avoidance for Unmanned Aerial Vehicles (UAVs) [4,5].

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UAVs operate in many different environments some of which are highly uncertain, dynamic and, in the case of military applications, often hostile. Current emphasis is on increasing the level of autonomy from pre-programmed path following to autonomous path re-planning to account for unforeseen events [6]. Such re-planning must be completed in real-time and follow some optimised strategy in order to ensure the safety and performance of the vehicle.

An additional requirement on automated path planners if they are to be accepted operationally, is that they must be trusted by human supervisors, i.e. it should be easy to understand the path planners decision making [7,8]. In the context of UAVs, the supervisor may be required to authorize a change to a pre-agreed flight-plan (Management By Consent, MBC) or to provide sufficient information about the decision making process so as to allow the operator to over-ride proposed changes (Management By Exception, MBE) for example in target allocation. The linguistic approach adopted throughout this paper provides an intuitive mechanism by which to convey information regarding the algorithm's decision making, i.e. it is *interpretable*.

There has been much discussion regarding the interpretability of fuzzy systems [9,10], although there remains no agreed definition [11] and consequently it remains a controversial topic [12–14]. Since fuzzy controllers were first proposed by Mamdani [15], the ability to provide an explanation or reasoning for a given decision has been a fundamental driver for using fuzzy sets to model complex systems. Interpretability can be considered as the property that indicates how easily an expert can comprehend the output of the system [13,16]. Although there is no agreed formal definition the following are seen as being characteristic of an interpretable system:

- fewer rules;
- consistency of rules (similar antecedents lead to similar consequents);
- simple rule antecedents containing only a few attributes;
- inclusion of only attributes that are familiar to the user;
- linguistic terms should be intuitively comprehensible (in terms of the membership functions);
- the inference mechanism should provide technically and intuitively correct results.

In light of these multiple criteria it is clear that interpretability is not a simple binary property but a function of the ability to comprehend a system's decision making. Unfortunately, it is generally accepted that there is a trade-off between accuracy and interpretability [12,13] although to further complicate the issue, in some instances over-fitting can lead to rules that are both less interpretable and with lower performance. In this paper we argue that Linguistic Decision Trees offer a good compromise between these two competing notions due to their underlying structure and clear semantic foundations. The method presented in this paper aims to maximise transparency but places slightly greater importance on the algorithm performance. However, it is accepted that alternative methods may offer higher performance at the expense of interpretability.

Path planning with obstacle avoidance is intrinsically NP hard [17,18]. Many solution methods have been studied including optimal control [19,20], potential fields [21,22], graph search [23–25], evolutionary algorithms [26,4] and even manually tuned fuzzy logic controllers [27].

In this paper, Mixed Integer Linear Programming (MILP) [28] is adapted as the reference planner, from which a Linguistic Decision Tree (LDT) will be trained. MILP offers high performance, and since it is used here only for off-line training, its comparatively heavy computational load is not a problem. The MILP planner is implemented within Model Predictive Control (MPC) [29–31] in which the planning problem is repeatedly solved on-line, and only the initial portion of each plan is implemented. This approach introduces feedback, to compensate for uncertainty, and can be proven to be stabilising [32] and to satisfy constraints. The result is a feedback guidance law for the UAV that ensures obstacle avoidance and offers high performance [5]. However, the on-line optimisation limits response speed and provides no justification for the specified output. This motivates cloning.

This paper proposes applying behavioural cloning to an optimized behaviour to combine the benefits of the optimizer's performance with the LDT's rapid decision making. The proposed controller prioritises a rapid decision period suitable for real-time implementation and places a high degree of importance on quality of the decision whilst seeking to maintain interpretability. Specifically the contributions of the paper are:

- an alternative partitioning of bearing attributes to account for circular domains;
- a more generalized Modal-LID3 algorithm (compared to [33]) to account for non-linear output functions;
- Lookahead-LID3 is proposed as a new approach to making predictions with an LDT in areas of high uncertainty.