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Submarine manoeuvring controllers' optimisation using simulated annealing and genetic algorithms

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Abstract

This paper is concerned with non-linear controller parameter optimisation for the diving and heading motions of a submarine model. The structure of the non-linear controllers used for these manoeuvres is derived from Sliding Mode control theory for decoupled single input, single output systems. The performance of these controllers depends on key design parameters. In this comparative study the values of these controller parameters are optimised using three different optimisation techniques. These are simulated annealing, segmented simulated annealing and genetic algorithms. The search properties of these algorithms are defined and compared in terms of simulated time domain results, convergence and saturation properties. These results are used to show the advantages and disadvantages of each optimisation technique.

Keywords: Sliding mode control; Submarine manoeuvring; Optimisation; Simulated annealing; Genetic algorithms

1. Introduction

From the early stages of their development, submarines have been used extensively by navies throughout the world (Burcher & Rydill, 1993). Their purpose has been the defence of marine interests for the country they serve and as technology has advanced the size and speed of these vessels have increased. This is particularly the case for the class of modern submarines referred to as 'hunter-killers', which are high-speed submarines that seek and destroy adversarial vessels. Since these vessels move at high speed there is a clear need for accurate navigational control so that they can execute commanded manoeuvres without causing damage to the crew, the vessel itself or any innocent party. Consequently, there is a requirement for automatic control systems that allow these vessels to manoeuvre effectively and safely. This paper describes the provision of such guidance capability by means of non-linear controllers that are derived from sliding mode (SM) theory (McGookin, 1997; Slotine & Li, 1991; Edwards & Spurgeon, 1998; Utkin, Guldner, & Shi, 1999; Fossen, 1994; Healey & Lienard, 1993; Healey & Marco, 1992).

SM control theory is based on non-linear switching principles, which provides inherent robustness properties that are able to compensate for the effects of unmodelled matched dynamics and external disturbances (Edwards & Spurgeon, 1998; Utkin et al., 1999; Fossen, 1994; Healey & Lienard, 1993; Healey & Marco, 1992). These robustness properties enable the controller to be effective over a wide operating range and exhibit better disturbance rejection capabilities than linear-based controller designs. This characteristic of SM controllers is provided by the non-linear *switching term* within the controller structure (McGookin, 1997; Slotine & Li, 1991; Edwards & Spurgeon, 1998; Utkin et al., 1999; Fossen, 1994; Healey & Lienard, 1993; Healey & Marco, 1992). It complements the control

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action of the nominal *equivalent controller*, which is usually a linear controller designed about a chosen operating point, by providing extended control action over a wider operational envelop (McGookin, 1997; Slotine & Li, 1991; Edwards & Spurgeon, 1998; Utkin et al., 1999; Fossen, 1994; Healey & Lienard, 1993; Healey & Marco, 1992). The extension of the control action enables the controller to compensate for unmodelled dynamics within the plant and external disturbances imposed by the surrounding environment. Consequently, the robustness aspect of this control methodology makes it ideal for marine navigation applications, e.g. submarine manoeuvring, where the complex interactions of the system dynamics are difficult to model and the external environment are extremely hostile. Both dynamical aspects cause vessels, such as submarines, to be difficult to control.

One of the most difficult and crucial aspects of non-linear controller design is determining suitable controller parameters so that the response of the system under control behaves in the required manner. This is particularly important with safety critical systems that have to perform correctly in order to ensure safe operation. Unfortunately, obtaining controller parameter values is usually a tedious and lengthy process, particularly if the designer is unfamiliar with the parameter interactions within the chosen controller structure. The need for automatic design methods has always existed but only recently has their development and use increased due to improved computing power. Consequently, it has been found that optimisation techniques such as simulated annealing (SA) (McGookin, 1997; Laarhoven, 1988; Laarhoven & Aarts, 1987; Metropolis, Rosenbluth, Rosenbluth, Teller, & Teller, 1953; Kirkpatrick, Gelatt, & Vecchi, 1983; Sharman & Esparcia-Alcazar, 1993) and genetic algorithms (GA) (McGookin, 1997; Goldberg, 1989; Ng, Li, Murray-Smith, & Sharman, 1995; Brooks, Iyengar, & Chen, 1996) are convenient techniques for obtaining near optimum design parameters and thus controller designs that perform satisfactorily for the given task.

With the emergence of these powerful optimisation techniques the supporters of these various approaches are making many claims and counter-claims. In this paper three such methods are examined for their performance in obtaining SM controller parameters for a linear submarine model (Miliken, 1984). The three methods in question are SA (McGookin, 1997; Laarhoven, 1988; Laarhoven & Aarts, 1987; Metropolis et al., 1953; Kirkpatrick et al., 1983; Sharman & Esparcia-Alcazar, 1993), segmented simulated annealing (SSA) (McGookin, 1997; McGookin, Murray-Smith, & Li, 1996; Atkinson, 1992) and GA (McGookin, 1997; Goldberg, 1989; Ng et al., 1995; Brooks et al., 1996). SA is chosen as a benchmark technique as it reported to be one of the more beneficial *hill-climbing* heuristics for parameter optimisation. Although this is a comparative study involving only one application it should provide some insight into the advantages and disadvantages of each of these optimisation methods. Particularly in terms of the convergence rate of the heuristics considered here.

The structure of the paper is as follows. Section 2 describes the application of SM controllers to specified submarine manoeuvring control scenarios (i.e. heading and depth changing). Section 3 outlines the three optimisation methods considered in this paper. The optimised controller responses from each of these methods and those obtained through manual tuning processes are compared in Section 4. This comparison is in terms of submarine and controller navigation performance, optimisation convergence properties and time taken to obtain the solutions. The final part of this paper discusses the conclusions drawn from this comparative study.

2. Submarine manoeuvring control

The application used to study both the SM control law and the optimisation techniques involves a tenth-order linear mathematical model of a military submarine. Like all submarines, this type of vehicle has freedom of movement within three dimensions, which allows motion in *six degrees of freedom* (i.e. both translational and rotational in each dimension) (McGookin, 1997; Fossen, 1994; Miliken, 1984; Gerther & Hagan, 1967). The resulting mathematical representation of the vessel describes the motion of a generic 'cigar shaped' submarine (Miliken, 1984), which is approximately 100 m in length and designed to be highly manoeuvrable. It has similar operational characteristics to the Los Angeles, Trafalgar and Swiftsure classes that are in service at present. Nevertheless the principles used in this investigation can also be applied to commercial submersibles and remotely operated vehicles (ROVs) since they have characteristics broadly similar to the above (Fossen, 1994; Healey & Lienard, 1993; Healey & Marco, 1992).

2.1. Submarine model

The mathematical representation used in this study is derived from the standard equations of motion for a submarine (Gerther & Hagan, 1967). These standard equations are obtained by considering the non-linear hydrodynamics of the vessel and defining its linear and angular velocities relative to body-fixed and Earth-fixed reference frames (Burcher & Rydill, 1993; McGookin, 1997; Fossen, 1994; Miliken, 1984) (see Fig. 1 and Table 1). Subsequently, the general form derived from these standard equations is non-linear. However, the