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A Review of Control Algorithms for Twin Rotor Systems

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Abstract: Twin rotor systems in many ways resemble helicopters and they are multiple-input multiple-output (MIMO) systems, highly nonlinear, and there is significant cross-coupling between their control variables. As a result, control of twin rotor systems is challenging and receiving great interest from a control engineering community. This paper presents a review of different control algorithms that have been published for control of a twin rotor MIMO system (TRMS) and a twin rotor aerodynamical system (TRAS). These control algorithms have been implemented through simulation using the systems' dynamic models and/or experiments on laboratory test beds. Initially, a brief review on an open loop control approach is given, and subsequently, a detailed review of closed-loop control approaches is presented.

Keywords: Control algorithms; Review; Twin rotor aerodynamical system (TRMS); Twin rotor MIMO system (TRAS).

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1. INTRODUCTION

Increased use of Unmanned Aerial Vehicles (UAVs) has led to amplified research interest in the use of laboratory test beds that can simulate complex aircraft manoeuvres and, into the embedded systems that control them. Improvement in the control of complex nonlinear systems also has a wide range of applications since many motion systems share several characteristics. The Twin Rotor MIMO System (TRMS) and its variant known as the Two Rotor Aero-dynamical System (TRAS) in many ways resemble helicopters and have attracted interest from researchers in recent years. They consist of a beam pivoted at its base in such way that it can move with two degrees of freedom (DOFs) in the horizontal (yaw) and vertical (pitch) planes. The main and tail rotors, driven by direct current (DC) motors, are attached to the ends of the beam perpendicularly to one another. Unlike conventional helicopters, the TRMS/TRAS are not equipped with a swashplate mechanism and aerodynamic thrust in is generated by increasing the rotation speed of the rotors. The result is a complex, high order nonlinear system with significant cross-couplings i.e. each rotor affects both the yaw and pitch angles.

Figures 1 and 2 show experimental TRMS and TRAS respectively, that have been used for verification of modelling and control algorithms. In addition to the cross-coupling effects, the TRAS/TRMS test bed is characterised by complex highly nonlinear functions with some inaccessible parameters (states) for measurement [1, 2]. The high order of the systems result in they having many resonant vibration modes which when excited, can lead to high oscillations or instability. The system is also under-actuated as there are only two control actions (the main and tail rotor torques) and for four controlled variables (the rotor speeds and the pitch and yaw angles). Figure 3 shows the TRMS/TRAS schematic drawing that illustrates major components of the systems.

Moreover, many assumptions and simplifications are also made in modelling of the system. This causes a problem of model uncertainty when applying model-based control and optimisation algorithms for the real plant. As aforementioned, the aerodynamic thrusts in the MIMO systems are produced by varying the rotor speeds, which cannot change instantaneously. The net effect is that the system effectively has a time delay, which is regarded as a major cause of instability in feedback systems [3]. All these, coupled with their under-actuated property, make the helicopter-like TRMS/TRAS a very challenging control problem.

This paper reviews and compares different control strategies proposed for the TRMS/TRAS in the literature. It is found that reviews of such systems are limited. Open loop and closed-loop control techniques implemented through simulation and real-time experiments on the systems are discussed with the purpose of identifying possible research gaps. The closed-loop controllers mainly involve linear, nonlinear, intelligent and augmented controllers, and the review is given according to these classifications.

Figure 1: Twin rotor MIMO system (TRMS) [1]

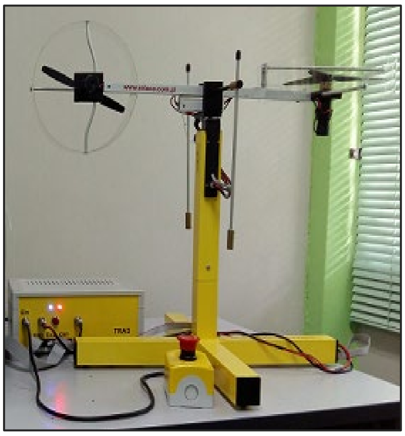

Figure 2: Twin rotor aerodynamical system (TRAS) [2]

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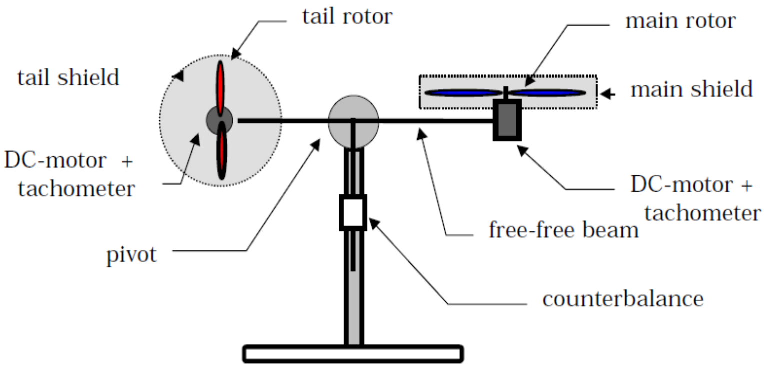

Figure 3. TRMS/TRAS component parts

2. CONTROL ALGORITHMS

Several control algorithms have been proposed for the TRMS/TRAS in the literature. The popular Proportional-Integral-Derivative (PID) controller and other linear control algorithms are the most common. Intelligent and nonlinear control algorithms have also been suggested by some researchers to improve the performance of the highly nonlinear helicopter-like systems. Figure 4 is a classification of the feedback control techniques that have been proposed for the TRMS/TRAS in the literature.

2.1 Open Loop Control

Open-loop (feedforward) control is often the preliminary step for the development of more complex feedback control laws. Feedforward control is used in the area of vibration suppression in the vertical (pitch) axis of the TRMS/TRAS. For this purpose, the method of input shaping, which generally involves convolving a desired input command with a sequence of impulses is applied. This strategy was first proposed for the TRMS in [4]. The technique, however, cannot achieve the main objective of position control and is often used in combination with feedback methods.

2.2 PID Control

The PID controller is the most common controller used in the industry [5] due to its relative simplicity and the well-established Ziegler-Nichols [6] method of tuning. Tuning the PID controller may also be done heuristically or by use of processes such as Genetic Algorithms (GAs) and particle swarm optimisation which minimise (or maximise) an objective function. Various types of PID based controllers have been proposed for the TRMS/TRAS in [7-20]. Juang et al. [11] reported the use of four PID controllers with independent inputs for the control of the TRMS in 2-DOF. The parameters of the controllers were obtained by a Modified method of a Real-type Genetic Algorithm (M-RGA) with a performance index as a fitness function.

One of the limitations of PID control, however, is that it has a narrow operating range and often leads to oscillations in higher order nonlinear systems. As such, for the helicopter-like system, PID is often augmented with other control algorithms to improve performance. PID has been used in combination with feedforward command shapers [8, 20] and fuzzy logic [10, 14, 17, 18]. In [21], nonlinear PID based on Active Disturbance Rejection Control (ADRC) with a general purpose observer was proposed to mitigate the cross-coupling effects in real time on the TRMS. Although the method achieved tracking of sinusoidal input waveforms, the results showed significant overshoots and long settling times. Moreover, the transient performance characteristics of the system under the proposed scheme were not investigated.

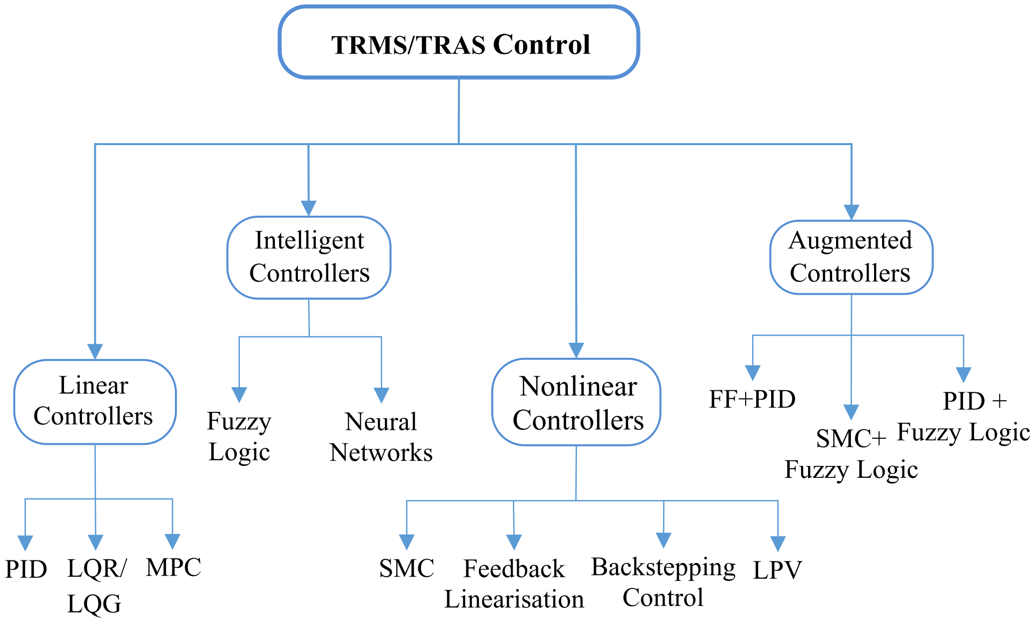

Figure 4. TRMS/TRAS control technique

2.3 Linear Optimal Controllers

Optimal control is a strategy involving the minimisation of an objective function to find a control law in order that an optimality criterion is achieved. In [22], a feedback Linear Quadratic Gaussian (LQG) compensator was proposed for the TRMS in 1-DOF. The system was further augmented with a command prefilter to moderate the requirement of high control energy and to reduce vibration. Other optimal controllers proposed for the system include the Linear Quadratic Regulator (LQR) in [23] using state feedback and in [24, 25] using output feedback. While these controllers can achieve robust performance, they give optimal rather than best results. Also, since LQR/LQG controllers are linear, they suffer from the problem of narrow operating ranges and have to be specifically tuned around the desired operating point.

Rahideh and Shaheed [26, 27] reported the application of Model Predictive Control (MPC) to the TRMS in which the nonlinear model was adaptively linearised during the prediction horizon. The linearised models from the TRMS were then utilised to form an objective function subject to inequality constraints based on the system's limits. MPC with instantaneous neural network linearisation was also proposed for the TRAS in [28]. While MPC has the advantage of handling system constraints, it is quite computationally expensive and requires high fidelity system models to achieve satisfactory performance.

2.4 Intelligent Controllers

Intelligent controllers are a class of control algorithms that employ various artificial intelligence computing approaches. Neural Networks (NNs) and fuzzy logic belong to this class of controllers and are commonly used in the control of nonlinear systems. This stems from the fact that intelligent controllers can be independent of complex nonlinear system models. Fuzzy control has been proposed for the TRMS in [9, 12, 29-31] and adaptive fuzzy control was suggested in [30]. Fuzzy logic, as mentioned earlier, has been employed in combination with PID control to improve system performance. It has also been proposed in combination with LQR in [32] and with Sliding Mode Control (SMC) in [33]. The drawback of fuzzy logic is that the performance depends on the number of membership functions, which can be very difficult to tune.

In [34], the real time implementation of an adaptive nonlinear model inversion controller was reported on the TRMS using artificial NNs. The feedback controller and the adaptive NNs were integrated to compensate for possible model inversion errors. It was reported that reasonable tracking response was exhibited in the presence of inversion errors caused by model uncertainty. This work was an experimental verification of the previous work [35] by the same authors in which only simulation results were provided. NNs have also been proposed to provide estimates of the TRAS' unmeasurable states in [36].

2.5 Non-linear Controllers

Nonlinear control refers to the control of systems that are nonlinear, time-varying or both. Almost all systems are nonlinear although most can be approximated by linear dynamic systems. There are, however, systems with intrinsic nonlinearities that cannot be approximated by linear systems and analysis and control is based on nonlinear systems [37]. As a result of high nonlinear behaviour, nonlinear control methods have also been popular for the control of the TRMS/TRAS.

SMC, due to its robustness, is among the most common nonlinear methods used in the control of the TRMS/TRAS. However, chattering is a problem associated with SMC as a result of the discontinuity of the control law. This motivated the comparative study of SMC chatter attenuation methods on the TRMS in [38]. Tao et al. [33] proposed a Fuzzy-Sliding and Fuzzy Integral Sliding Controller (FSFISC) to position the yaw and pitch angles of the TRMS. The system was pseudo-decomposed into a horizontal subsystem (HS) and a vertical subsystem (VS) with the coupling effects considered as uncertainties. Simulation results showed that the chattering phenomenon experienced in SMC was drastically reduced while the system remained robust to external disturbances. Mondal and Mahanta proposed a second order SMC [39] and Adaptive Second Order SMC (ASOSMC) in [40] for the TRMS to reduce the undesired chattering effect. Although simulation results with the proposed SMCs in [33] and [40] gave better performance characteristics than the M-RGA PID in [11], calculation of the control laws was quite complex and tracking of sinusoidal input waveforms could be further improved.

While real time implementation of terminal SMC on the actual TRMS was achieved in [41], results therein showed quite long settling times. Implementation of SMC with a nonlinear state observer to estimate the unmeasurable states was also reported in [42] for the TRMS. SMC has also been proposed for the TRAS by experiment with an extended Kalman filter [43] and in [44] using a sliding mode disturbance observer. The obtained results in [44] showed good tracking of sinusoidal waveforms albeit with some oscillations around the peak regions having low rotor speeds.

Application of the nonlinear extension of the classical robust H-infinity controller [45] and nonlinear robust L_2 control [46] have also been reported on the TRMS. The control structures used could be interpreted as nonlinear PID controllers with time varying gains. The robustness properties of these methods make them readily applicable to the cross-coupled MIMO system. However, results in these works were only given for piece-wise constant references with ramp-like changes and tracking of time varying waveforms was not investigated.

Feedback linearisation, a common technique used to control a class of nonlinear systems has also been proposed for the TRMS. It involves cancellation of the system's nonlinearities and then applying well established linear control methods externally on the resulting linear system. In [47], 2-step switched feedback linearisation was proposed to extend the operation range of the TRMS in 1-DOF. An LQR algorithm was employed to serve as the external controller. Feedback linearisation was also proposed for the TRMS via output feedback with a local state observer [48] and with an extended Kalman filter [49] to observe the unavailable states. Only simulation results were given in [48] while the output responses in [49] showed significant errors in tracking a sinusoidal reference.

Following the earlier work [50], the quasi-Linear Parameter Varying (LPV) modelling, identification and control of the TRMS was reported in [51]. Using the high fidelity model proposed by Rahideh and Shaheed [52], the nonlinear model of the TRMS was first transformed into a discrete time polytopic quasi-LPV model. An LPV state observer was then used to provide estimates of the unmeasurable states and integral action was added using state augmentation proposed in [53]. Although the error was minimised, integral action might possibly have been responsible for oscillations noticed in the experimental results provided.

Backstepping is a systematic nonlinear control design methodology and is a natural choice for the control of nonlinear, under-actuated and triangular systems [54] like the TRMS/TRAS. That is, systems in which the un-actuated states are controlled by the interaction with the actuated states in a cascaded manner. Adaptive backstepping along with a neuro-adaptive observer [36] and with a Luenberger type observer [55] have been suggested for the TRMS. Real time results in [36] showed significant errors in tracking of sinusoidal waveforms while high overshoots resulted from step changes to the reference in [55]. Integral backstepping with a disturbance observer and command filtered compensation (where virtual backstepping control derivatives are generated with low pass filters) was proposed for the TRAS in [56]. Results therein showed good tracking of sinusoidal signals but the transient response performance characteristics were not examined with step changes in the reference.

In [57], a simplified nonlinear backstepping control method for fast trajectory tracking of a 2-DOF TRAS has been proposed. The control design considers the system as having relative degree 2, resulting in a much less complex 2-step backstepping control law requiring partial state feedback. Real time experiments show good tracking ability of the controller to different input waveforms within a wide operating range. In another work, a dual boundary conditional integral backstepping control of a TRMS was proposed [58]. The system was decoupled into the vertical subsystem and the horizontal subsystem, and an integral backstepping controller was designed for each subsystem with the cross couplings considered as uncertainties. An adaptable integral gain law was formulated to provide integral action conditionally within two (outer and inner) boundary layers, based on the output tracking error and reference signals. Simulation results showed that the proposed approach achieves robust output regulation in the presence of the system's uncertainties and external disturbances whilst maintaining a good transient response. The technique was further improved in [59] by utilising a switching technique on the TRAS in real time. Experimental results therein show improved transient and tracking performances, and robustness in the presence of the coupling effects and an external wind gust. Recently, a switched-step integral backstepping control scheme was designed to improve immunity to measurement noise and to increase the energy efficiency of conventional backstepping for TRAS control [60]. The controller was realized by switching between two candidate controllers obtained at different steps of the iterative backstepping design process. Experiments show that in addition to a reduction in power consumption, the controller reduces saturation of the control signal and visible motor jerking in contrast with conventional backstepping. The controller was also robust to an external disturbance.

2.6 Augmented Controllers

Augmented control here refers to combining two or more control methods to give improved performance. This need arises as it is often difficult for a single control law to give overall satisfactory performance in practice. Augmented controllers proposed for the TRMS/TRAS include input shaping feedforward approaches in combination with feedback methods [8, 20, 22]. These were proposed to suppress vibrations in the pitch axis of the system while achieving position control. Other researchers proposed fuzzy logic compensation in combination with PID [9, 10, 14, 18] and in combination with SMC [33].

While controller augmentation can improve performance, it leads to additional delay in the system response when feedforward input shaping methods are used. Controller augmentation also invariably results in added complexity (and tuning difficulty) of the control law especially when methods like NNs (which require learning) and fuzzy logic compensation are employed as observed in [33].

2.7 Comparisons

An examination of the various aforementioned control approaches on the TRMS/TRAS indicates several methodologies have been successfully applied to the system. Input shaping control has mainly been used for vibration suppresion in the vertical axis of the systems. However, as an open loop control, the controller was not able to achieve the objective of position control. While the PID control has the advantage of simplicity and requires only output feedback, the performance of PID controllers for the highly nonlinear systems often needs improvement by controller augmentation, resulting in added complexity. Other linear methods like LQR, LQG and MPC require linearised models of the plant about specific operating regions. These techniques, therefore, suffer from narrow operating ranges especially when the linearised model is derived from an imprecise nonlinear model.

Intelligent approaches like fuzzy logic and NNs, on the other hand, have the advantage of not requiring a system model. These techniques, however, are rarely used in isolation but in conjunction with other control methods either serving as compensators or as adaptive parameter tuners. While nonlinear control techniques like SMC, feedback linearisation and backstepping result in improved performance, the control laws are complex and require estimation of unmeasurable states. This can result in degraded performance, especially in real time control of systems affected by measurement noise.

3. CONCLUSION

This paper has presented a review of the control techniques proposed for the TRMS/TRAS. The open loop control has mainly been used for control of rotor vibration. Besides, several closed-loop control approaches including linear, nonlinear, intelligent and augmented controllers have been designed for input tracking of the twin rotor system, and to achieve a robust system towards parameter uncertainties and external disturbances. Comparisons of the methods in the literature that are concerned with improving the performance and efficiency of the system have also been discussed.

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DECLARATION OF CONFLICTING INTERESTS

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