ABSTRACT

The topic of underactuated systems has garnered much attention in the field of control systems in recent years. These systems pose a unique challenge as they have fewer control inputs compared to the number of degrees of freedom. The ability to stabilize and accurately track a desired trajectory is crucial for the successful operation of these systems. The aim of this thesis is to investigate various techniques for improving the stabilization and trajectory tracking of underactuated systems. Through a combination of theoretical analysis and simulation studies, this thesis explores novel approaches for enhancing the performance of these systems. The findings of this research have the potential to contribute to the advancement of control systems technology and to improve the design and implementation of underactuated systems in practical applications such as robots, Segway, the human posture systems, Pendubots, the launching of a rocket, unmanned aerial vehicles, and autonomous underwater vehicles.

The primary objective of managing underactuated systems is to stabilize them at different operating conditions and guarantee accurate trajectory tracking. This necessitates the development of control algorithms that strike a balance between stability and performance. Choosing a control strategy that emphasizes stability may lead to poor performance in trajectory tracking, while prioritizing performance may cause instability. Earlier, to tackle the challenges associated with underactuated systems, various control techniques are employed, such as feedback linearization, sliding mode control, and adaptive control. These methods consider the system's dynamics and the available control inputs to achieve stable and accurate control. Despite the unique challenges posed by underactuated systems, they can be controlled efficiently through meticulous design and implementation of suitable control algorithms. The

research on underactuated systems is ongoing, and new and improved methods are continually being developed.

The benchmark Cart-Inverted Pendulum System is used here to analyse the performance of Linear Matrix Inequality based State Feedback Controller and the Linear Quadratic Regulator based optimal controller. This benchmark system poses two control problems. The first control problem is to swing up the pendulum from its initial rest position and the second control problem is to stabilize the pendulum in the upright position which is highly unstable in nature, while tracking a desired trajectory with minimum tracking error. The stabilization problem of the cart-inverted pendulum has resulted in a variety of advanced control algorithms. Chronologically starting from a simple State Feedback Controller (SFC) to complex convex optimization problems are designed and evaluated for the stabilization problem of this benchmark system. This research work focusses on the Linear Matrix Inequalities (LMI) based State Feedback Controller and the Linear Quadratic Regulator based State Feedback Controller for the stabilization of the pendulum in the upright position for the Cart-Inverted Pendulum system.

Due to recent advancements in the processing capability of computers, the linear matrix inequalities in control are again gaining significance which otherwise are difficult and time consuming to solve manually. The objective is to formulate a Linear Matrix Inequality based control problem, the solution of which is then used to find the state feedback gain that is used in the State Feedback Controller. In this research work, a simple LMI based SFC is first designed using the basic Lyapunov method. In the existing LMI controller design, the inequality conditions are added to include the proper selection of Linear Matrix Inequality region to get the optimal response by Muhammad (2018). Also, the selection of LMI region is by iterative method which is cumbersome. To overcome the iterative method, optimization algorithms are employed in this research work to narrow down the LMI region which bring about the optimal performance of the State Feedback Controller.

Several optimization techniques inspired by nature have been developed by researchers. In this research work, the Ant Lion Optimizer (ALO) is used to tune the Linear Matrix Inequality based State Feedback Controller to select proper LMI region which in turn gives the optimal state feedback gains for the proposed control problem. Unlike Particle Swarm Optimization (PSO) and its variants, the Ant Lion Optimizer does not require any pre-requisite information relating to the parameter initialisation. The parameters such as inertial weights and velocity in the PSO method need to be properly chosen else there are more chances for the optimization to get trapped with the local optimum. Since the ALO method does not have such constraints, it results in a better global optimum value within the search space. The proposed ALO tuned LMI based SFC is compared with the LMI based SFC without optimization and Adaptive Particle Swarm Optimization (APSO) tuned LMI based SFC. The proposed controllers' performance is experimentally validated, and the results show that the ALO tuned LMI based SFC has a better transient response while reducing the desired trajectory tracking error by 41.97%, in addition to the stabilization of the inverted pendulum than the LMI based SFC without optimisation. Thus, the addition of proposed optimization algorithms in tuning the LMI region improves the performance of the LMI based State Feedback Controller.

Further, researchers have tried to improve the performance of the ALO algorithm by hybridizing it with the positives of other optimization algorithms. Hongping Hu *et al.* (2019) have used the velocity update equations of PSO as the elitism operator of the ALO algorithm. As there are many variants of APSO showing improved results over PSO, in the second work, the ALO algorithm is hybridized it with the adaptive variant of PSO proposed by Zhan *et al.* (2009). As a result, the proposed Adaptive Elite – Ant Lion Optimizer (AE-

ALO) is the second work taken up in this research. The limitations of choosing proper initial parameter selection in PSO are overcome by adaptively updating the parameters based on the search results during every iteration. To test the efficacy, the proposed AE-ALO is tested against the standard benchmark unimodal and multi-modal functions. The results show AE-ALO is better than several existing optimization algorithms. The developed algorithm is then used to tune the Linear Matrix Inequality based State Feedback Controller for the stabilization of CIPS. The results obtained indicate that the AE-ALO tuned LMI based SFC shows improved performance in different operating conditions over the ALO tuned LMI based SFC and the controllers in comparison.

Another work taken up for research is the Linear Quadratic Regulator (LQR) based SFC which is an optimal control method for the stabilization problem that achieves robust stabilization of the inverted pendulum even in the presence of disturbance (Vinodh Kumar & Jerome, 2013). In this method, the Algebraic Riccati Equation (ARE) is solved to get the closed-loop feedback gain of the system. Here, the selection of weighting matrices affects the solution of the ARE, which in turn affects the closed-loop performance of the system. As there are no standard procedures to select the weighting matrices of the LQR and as the performance of the method hinges on the random initial selection of weights, the solution of the ARE in LQR is addressed by researchers using varied optimization algorithms. The efficacy of the proposed AE-ALO algorithm is evaluated in optimizing the control problem by tuning the weighting matrices of the LQR. The AE-ALO tuned LQR based SFC is found to have superior transient response and reduce trajectory tracking error by 10.97% while stabilizing the inverted pendulum better than the ALO tuned LQR and APSO tuned LQR in comparison.