Towards Sophisticated Control of Robotic Manipulators: Experimental Study on a Pseudo-industrial Arm

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Robotic manipulators have reshaped industrial processes. Scientific community has witnessed ever increasing trend of robots deployment to accomplish various tasks in industry. Complex nature and constrained requirements may demand non-trivial control approaches. This paper deals with design, simulation and hardware realization of two sophisticated control strategies; Computed Torque Control (CTC) and Variable Structure Control (VSC) on a pseudo-industrial manipulator with six Degree Of Freedom (DOF). Based on the derived kinematic and dynamic models of the robot, control laws have been formulated, which are then subjected to various test inputs in simulation to characterize the tracking performance. The simulation results are then validated by implementing control laws on custom-developed pseudo-industrial AUTonomous Articulated Robotic Educational Platform (AUTAREP). Experimental results dictate effectiveness of the control strategies to track a desired trajectory.

Keywords: robot control, manipulator, robust laws, industrial robots

INTRODUCTION

Today robots are being deployed to accomplish tasks having strict requirements of accuracy, precision, repeatability, mass production and quality. Major breakthrough was reported with the advent of feedback control systems and self-correcting mechanisms. The development of multi-Degree Of Freedom (DOF) manipulators contributed significantly towards the modern robots. Industrial robots are primarily multi-DOF anthropomorphic manipulators. The course of the past few years has witnessed a large rise in the use of industrial robots. This trend is anticipated to be continued as highlighted in [1].

Performance of a robotic manipulator is characterized by a well-defined control approach [2]. Classical or trivial control strategies are usually based on linear control laws while modern approaches are nonlinear in nature. The approach to control a multi-DOF manipulator must be robust enough to cope with the effects of inherent nonlinearities and coupling in the robot dynamics [3-5]. Classical approaches suffer from various issues, which can be avoided by merging these with advanced control strategies or using an advanced strategy in standalone.

Control of multi-DOF robotic manipulators is a vital research area today. However, most of the reported research works are either limited to implementation of linear control approaches or simulation of sophisticated control strategies. In contrast, the present work investigates the advanced approaches like Computed Torque Control (CTC) and Variable Structure Control (VSC) from simulation viewpoint as well as physical realization on a custom-developed AUTonomous Articulated Robotic Educational Platform (AUTAREP).

CONTROL DESIGN

The study of manipulators for diversified applications has highlighted the need of sophisticated algorithms for their control and trajectory planning. The objective in the design of robotic manipulators is to control both the position and the orientation of the tool in 3D workspace.

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Scientific community reports both classical and robust strategies for robot control. Considering classical approaches, Iqbal et al. have proposed Proportional Integral Derivative (PID) controllers for mobile robots [6] and multi-DOF serial link robotic exoskeletons [7, 8]. Role of PID control in industrial automation has been presented in [9], which formulates a nonlinear PID control law to ensure Global Asymptotic Stability (GAS). Classical approaches, when combined with modern control strategies, improve transient response in uncertain scenarios as highlighted in [10]. Combining VSC with PID and adaptive control strategies, Jingmei et al. have improved precision in trajectory tracking of a robotic manipulator [11]. Chattering has been reduced with the increased system response time. Tahir and Jaimoukha have proposed a model predictive robust controller [12] for linear discrete-time systems subjected to polytopic constraints and bounded disturbances. The proposed control approach is novel in that the outer controller incorporates state-feedback structure where feedback gains are considered as decision variables in online optimization [13].

PID has been the main workhorse in industrial sector. However, research community has recently shown an active interest in the development and applications of nonlinear control methodologies applied to robotic manipulators. A comprehensive review of control strategies for manipulators is reported in [3].

The overall control problem consists of kinematic and dynamic modeling, followed by the design of control law. Kinematics of AUTAREP manipulator has been derived in [14] using Denavit-Hartenberg (DH) representation while the system dynamics has been modeled in [15] using Euler Lagrange equation (1).

\[ \tau = M(q, \dot{q})\ddot{q} + V(q, \dot{q}) + G(q) + f(q) \]  

where \( M(q, \dot{q}) \) is a 4×4 inertia matrix, \( V(q, \dot{q}) \), \( G(q) \) and \( f(q) \) are 4×1 vectors of Coriolis centrifugal force, Gravitational force and Frictional force respectively. \( \tau \) is the 4×1 torque vector applied to the joints of the robot and \( q, \dot{q} \) and \( \ddot{q} \) are 4×1 vectors for angular position, velocity and acceleration respectively.

This paper deals with two modern control strategies namely CTC and VSC.

2.1 CTC

CTC is a special type of feedback linearization technique with symmetric, constant and positive definite controller gains. CTC can be utilized effectively in case of known nonlinear dynamic parameters and uncertainties. For CTC law, the expression for the manipulator system in (1) can be written as in (2).

\[ \tau = M(q, \dot{q})(\ddot{q} - 2\lambda \dot{e} - \lambda^2 e) + V(q, \dot{q}) + G(q) \]  

where the vector \( q = [q_1 \ q_2 \ q_3 \ q_4]^T \) corresponds to the first four joints of the manipulator. \( q_d, \dot{q}_d \) and \( \ddot{q}_d \) are desired joint angle position vector \( \dot{q}_d = [q_{d1} \ q_{d2} \ q_{d3} \ q_{d4}]^T \) and its 1st and 2nd derivatives respectively. \( e = q - q_d \) is the error signal with \( \dot{e} \) as its 1st derivative. \( \tau \) is the required control output and is represented by \( \tau = [\tau_1 \ \tau_2 \ \tau_3 \ \tau_4]^T \). The gain matrix \( \lambda = \text{diag}\{\lambda_1 \lambda_2 \lambda_3 \lambda_4\} \) can be used to alter the system dynamics.

2.2 VSC

VSC finds potential in eliminating uncertainties and disturbances present in the system. A switching surface is designed and the main task of the controller is to drive the system states to this surface. The system then remains on the switching surface to reduce disturbances and modeling uncertainties. VSC is a robust control strategy which uses high frequency switching control for altering dynamics of the nonlinear system. VSC law for the robotic manipulator, by choosing the sliding manifold \( S = \dot{e} + Ce \), is given in (3).

\[ \tau = M(q, \dot{q}) (\ddot{q} - C \dot{e}) + V(q, \dot{q}) + G(q) - K \text{sgn}(Ce + \dot{e}) \]  

where the matrices \( C = \text{diag}\{c_1 \ c_2 \ c_3 \ c_4\} \) and \( K = \text{diag}\{k_1 k_2 k_3 k_4\} \) are switching gain constant and sliding surface constant respectively and can be changed to alter the system dynamics.

2 SIMULATION

The controller s-functions have been developed in MATLAB/Simulink based on the derived dynamic model of the manipulator. Various desired trajectories including step, sinusoidal and ramp have been applied to analyze robustness and effectiveness of the proposed
control laws. The overall effect of the plant has been investigated by choosing different values of the system constants i.e. \( \lambda \) for CTC and \( C, K \) for VSC.

In case of CTC, varying \( \lambda \) revealed that the performance of the system improves by increasing the value of \( \lambda \). For example, considering second joint (shoulder), the simulated step response is used to investigate the effect of assigned \( \lambda_2 \) values. Keeping \( \lambda_1, \lambda_3 \) and \( \lambda_4 \) as constant (unity), step response of shoulder joint for \( \lambda_2 = 1, 2, 3, 4 \) is illustrated in Fig. 1a with the corresponding torques plotted in Fig. 1b. No overshoot is observed in any case. However significant difference in rise time and settling time is noticeable. When \( \lambda_2 \) is increased from 1 to 4, the rise time reduces from 7.13s to 1.97s while the settling time reduces from 5.20s to 1.86s at \( \pm 5\% \) of the desired joint angle. The initial magnitude of torque (25.9Nm) is required to keep the shoulder joint at its initial position against the gravitational force. The final magnitude of torque is 12.9 Nm.

(b) Corresponding torques

Considering the case when all joints are moving simultaneously, same value (\( \lambda = 4 \)) has been set for each joint of the manipulator. The corresponding step responses and plots of torque are shown in Fig. 2. With slight difference in behaviour of various joints, it is inferred from the results that various joints exhibit different torque requirements. Shoulder joint requires final torque of 5.4Nm which is due to the movement of other joints. The initial and final torque requirements of base joint are 0Nm due to zero gravitational effect. The same requirements in case of elbow joint are 5.9Nm and 3.1Nm respectively. Having little gravitational effects in wrist joint, initial and final torque requirements are 0Nm and 0.2Nm respectively.

The equivalent control is designed such that the states of the system are on the sliding manifold, which is defined as \( S = Ce + \dot{e} \) where \( C \) must satisfy the Hurwitz condition, i.e. \( C > 0 \).
On the other hand, the Lyapunov function $L = 0.5 S^2$ restricts $K > 0$. The corresponding entries of $C$ and $K$ matrices cannot be selected independently without violating above conditions [16] due to the joints’ coupling effects.

Considering first joint (base), with $c_1 =4$, step response for different values of $k_1$ is illustrated in Fig. 3. Comparing the responses, it is clear that the waveform corresponding to $K_1 = 8$ exhibits relatively less rise time and settling time. Thus, the optimum response is achieved with $k_1 = 8$.

![Fig. 3. VSC step response of base joint for different value of $k_1$](image)

With tuned values of $C$ and $K$ matrices, the step response of various joints moving simultaneously is shown in Fig. 4a. It can be inferred from the plot that elbow joint and wrist joint even after reaching their desire position, are not stable until shoulder joint reaches its final position and gets stabilized. This is in accordance with coupling effects of the joints. Looking at the applied torque plot shown in Fig. 4b, the switching effect is observable.

![Fig. 4. Joints moving simultaneously (a) VSC step response (b) Corresponding torques](image)

### 3 EXPERIMENTAL SETUP AND RESULTS

To validate the simulation results, experiments have been conducted on an indigenously developed AUTAREP illustrated in Fig. 5. It is a mini-industrial open-source, novel and complete robotic system that finds potential in training interns, imparting mechatronics concepts to engineering students and validating advanced algorithms for trajectory generation and control, object manipulation and grasping, path planning etc [17].

The mechanical system of the platform is built around a 6-DOF serial robotic manipulator. The arm’s geometrical configuration resembles that of the human arm. Six precise DC servo motors actuate the robot while sensory system comprises of encoders and Force Sensing Resistor (FSR) in addition to an on-board camera. Primary features of AUTAREP are mentioned in [15]. The designed electronic system mainly consists of an embedded controller DSPIC33F and 6A/50V rated custom-designed motor drivers. The hardware and software architectures of the platform are detailed in [17].

![Fig. 5. AUTAREP – A custom-developed pseudo-industrial framework](image)
First the CTC law has been implemented on the manipulator. The trajectory tracking performance for different gains ($\lambda_i$) has been observed for base, shoulder, elbow and wrist joints with each joint moved at a time. Fig. 6 illustrates step responses of shoulder joint and elbow joint with $20^\circ$ set as the desired angle.

CTC simulation and hardware implementation both endorse that increase in gain-constant results in better performance by improving the system’s response. In contrast to simulation, it is visible in hardware results that for same value of gain constant, each joint exhibit slightly different response. This is due to the fact that each joint’s motor produces different torque and speed.

![CTC step response of shoulder joint and elbow joint](image)

Fig. 6. CTC step response of (a) Shoulder joint (b) Elbow joint

To realize VSC law on the physical manipulator, after simple trajectory tracking experiments, the coupling effect has also been studied. Joints have been moved simulatneously as well as independently to observe this effect. Results are illustrated in Fig. 7. It can be inferred from Fig. 7a that shoulder joint exhibits overshoot for a longer period of time and settles to the reference angle after settling of elbow joint. The coupling effect on the shoulder joint causes it to move faster.

VSC simulation and hardware implementation both confirm strong coupling effect. In contrast to simulation, the elbow joint in hardware implementation does not come to rest until the shoulder joint is stabilized at its destination. This is quite expected due to the fact that a link near to the fixture or base is less exposed to mechanical stability.

![Step response of base, shoulder and elbow joints](image)

Fig. 7. Step response of base, shoulder and elbow joints when the joints are actuated (a) At the same time (b) One at a time

4 CONCLUSIONS

This paper presents design, simulation and hardware realization of CTC and VSC strategies. Simulation results have been verified through experimental implementation on a physical platform. Trajectory tracking results witnessed that the derived laws can effectively track the desired reference input for both non-linear control.
methods. The coupling effects present in the joints are less visible in simulation but are more prominent in hardware implementation. Future work includes task dependent performance comparison of robust control strategies on multi-DOF robotic manipulators.

REFERENCES


