The Quanser Platform for Control Systems Research Validation

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Introduction

Contemporary research in control covers extensive ranges of theoretical, computational and application fields. Since control is one of the most broadly applicable modern engineering methodologies, researchers in virtually all of the engineering disciplines apply its techniques to realize ever more complex engineering systems. Nevertheless, from a very practical perspective, it is often challenging to develop an effective research regimen that includes an advanced theoretical and algorithm framework and real-world implementation. Quanser devices offer a highly efficient platform for bridging this theory-implementation gap.

In a perfect world, researchers should be able to test their control strategies and algorithms directly on a complete prototype system. In reality, of course, such an approach would be prohibitively expensive and generally ineffective due to the exploratory nature of research. Modern control researchers have adopted a framework of hardware in the loop (HIL) implementation of the control system that integrates a physical system [the plant] that offers dynamics of sufficient realism for physically relevant testing, and a real-time computational and modeling framework that allows for rapid testing of algorithms and concepts. Using such a combination, researchers are able to readily validate their research concepts with a physical system. The Quanser platform is the de facto commercial standard for control research validation along this line for a broad range of applications including flight control, unmanned vehicle applications, biomedical and rehabilitation robotics, haptics, industrial robotics and automation, and more.

The Quanser Method™

The essential plant hardware readily adapts to a core engineering workflow that offers a holistic approach to control system design and prototyping. This workflow is often referred to as the Quanser Method™. The Quanser Method integrates:

- Mathematical modeling
- Computer simulations
- Data collection and system identification
- Control design
- Parameter estimation
- Real-time systems
- Code generation
- Hardware in the loop simulation
- Optimization
- Implementation and deployment

To support this rich methodology, Quanser systems embody the following fundamental qualities:

- **High precision components.** They ensure repeatability and deterministic dynamics to minimize the introduction of data artifacts.
- **Modular and open architecture design.** It enables rapid reconfiguration of test rigs to quickly adapt to new experiments and design refinements.
- **Full utilization of digital and software methodologies.** Quanser software covers both low level, real time control computations to ensure absolute precision, and high level application tools to quickly develop high fidelity models. Additionally, Quanser systems support the full range of modern digital platforms from general-purpose computers, to specialized real-time control computers for autonomous applications, and even modern mobile device platforms.
- **Application coverage.** The Quanser technology collection is the most extensive platform for control, mechatronics and robotics research. Within a common technological and software framework, researchers can engage in progressive research in fields as technically different as biomedical, energy, defense, agricultural, aerospace and automotive engineering to name a few.
- **Complete toolchain.** Quanser plants are also supported by optimized data acquisition [DAQ – Quanser and third party], amplifiers, and software components compatible with industry-standard software such as National Instruments LabVIEW™ and MATLAB®/Simulink® from The MathWorks®.
Research Examples

This article presents a survey of theoretical and application research topics from various institutions that have deployed Quanser equipment to validate their research concepts. At the heart of these examples are some of the most important control topics that feed into a critical application areas. In particular, the topics are:

I. **Adaptive Control**: Helicopter flight control using Quanser 3 DOF Helicopter
II. **Nonlinear Control**: Sliding mode control using Quanser Rotary Servo Base Unit
III. **Robust Control**: Gyroscopic motion control using Quanser Rotary Gyro/Stable Platform
IV. **Optimal Control**: Model predictive control with fluid tanks using Quanser Coupled Tanks
V. **Intelligent Control**: Fuzzy logic control in space robotics using Quanser Rotary Flexible Link
VI. **System Identification**: Development of a low cost IMU for UAV applications using Quanser 2 DOF Helicopter

Figure 1 presents a larger sample of Quanser equipment and their successful application in the above key control research areas.
I. Adaptive Control: Helicopter flight control

Some of the most significant research developments in control have come from aerospace applications. For example, with the recent popularity of unmanned aerial vehicles (UAVs), new or refined control schemes are needed and are being developed. Professors often need a platform on which to test their controller before implementing it on an actual UAV. This example summarizes how researchers are testing their new controller concept on a model tandem helicopter.

One of the challenges with helicopter control is the inherent nonlinearities, cross-couplings, and uncertainties in the dynamics of the system. In their paper (Ishitobi M. a., 2010), the authors, representing Kumamoto University in Japan, investigated a nonlinear adaptive control scheme to compensate for these effects and chose the Quanser 3 DOF Helicopter as their testing rig. The Quanser 3 DOF Helicopter is a tandem-rotor bench top aerospace system that was developed in conjunction with the Massachusetts Institute of Technology. The device is an under-actuated system. The helicopter body can move in the three-dimensional space using two motorized rotors to drive it up, down, and around the base (rotating freely 360 degrees using a slip ring mechanism).

PID-based control methods in these applications do work, but they may not compensate for the couplings and uncertainties very well - especially on a UAV where these can change depending on the environmental conditions. Robust (e.g. H-infinity) and adaptive methods are therefore often considered for helicopters and other aerial vehicles. In this case, the authors propose a nonlinear model following control system. In this paradigm, the output of the state feedback controller causes the nonlinear device being controlled to track the output of a reference model. However, because the dynamics of the helicopter cannot be decoupled via static state feedback, a nonlinear control-based structure is used instead. This is a new way of doing things and the goal of the paper is to demonstrate its feasibility by implementing it on the 3 DOF Helicopter.

In order to deal with uncertainties, a parameter identification scheme is introduced. The original identification paradigm that was tested relied on velocity and accelerations, which were computed using first-order filters. This does not yield satisfactory tracking results. The velocity and accelerations were not accurate enough for the parameter identification algorithm and caused poor parameter estimates. The revised identification scheme applied integrals to the dynamic model equations and removed the need for acceleration and velocity signals. With accurate parameter estimates, the control obtained satisfactory tracking results. To minimize tracking error even further, extra terms were added to the dynamic model to express model uncertainties and external disturbances.

Other published papers on adaptive control that use Quanser equipment:

- Gain-scheduled proportional-integral-derivative (GS-PID) control and model reference adaptive control (MRAC) strategies are designed and implemented on the Quanser Qball UAV [Sadeghzadeh, Zhang, and Rabbath, 2011].
- Adaptive iterative learning control designed for the Thermo CRS Robot through the open-architecture integration and RCP software provided by Quanser [Tayebi and Islam, Adaptive iterative learning control for robot manipulators: Experimental results, 2006].
- Adaptive control based on the passification design method and the Implicit Reference Model approach is experimentally tested on the Quanser 3 DOF Helicopter [Andrievsky, Peaucelle, and Fradkov, 2007].
II. Nonlinear Control: Implementation of sliding mode control

Nonlinear control covers a broad range of topics. In this section, we highlight the use of sliding mode control (SMC). Sliding mode control simplifies the control design by reducing the order of a complex system and is robust against uncertainties. For these reasons sliding mode has been implemented on a wide variety of systems, from robot manipulators to triple inverted pendulums.

There are, however, some practical challenges with sliding mode control. First, the control is discontinuous. Therefore before it can be implemented on a system, the control signal must be smoothed out (e.g. using a boundary layer). Applying high-frequency signals to actuators can, over time, lead to hardware issues or failures. It can also excite un-modeled dynamics in the system. Secondly, if the upper bounds to the uncertainties and disturbances are over-estimated then SMC tends to over-compensate for uncertainties and have large control signals, which can saturate the actuators and cause unexpected behavior in the system.

The authors in [Ginoya, Patel, Shendge, and Phadke, 2011] of the College of Engineering, Pune, India, implement an inertial delay observer with model following sliding mode control. In this paradigm, the states are estimated using a linear observer and the parametric uncertainties and disturbances are estimated using an inertial delay observer. The bounds on the disturbances and uncertainties are found adaptively, which is then used in the SMC, and prevents large control signals. The resulting control signal is also continuous.

To test the performance of this type of sliding model control, the authors use the Quanser Rotary Servo Base Unit [SRV02]. The SRV02 is a geared servo system with encoder and potentiometer sensors to measure the load shaft position as well as a tachometer to measure its speed. The system is interfaced with a Quanser DAQ and controlled through the PC using Quanser RCP software, which makes it easy to implement their SMC control. By attaching different inertial loads [disc, bar] on the external gears of the servo and adding parametric uncertainties, the authors were able to validate how well the observer and control performed under different load conditions. They found that, unlike standard sliding mode control, this strategy did not require large control signals to compensate for uncertainties.

Other published papers on nonlinear control that use Quanser equipment:

- The Quanser 2 DOF Helicopter used to test motion primitives generated by an algorithm inspired from a biological environment [Perk and Slotine, 2008].
- Design and real-time testing of an attitude controller on the Quanser UFO experiment [Wu, Liu, and Zhu, 2003].
- Use matching condition to find control candidates for the Quanser Ball and Beam system [Andreev, Auckly, Gosavi, Kapitanski, Kelkar, and White, 2002].
- Experimental implementation of a feedback control law derived using the method of controlled Lagrangians is tested on the Quanser Linear Inverted Pendulum system [Reddy, Whitacre, and Woolsey, 2004].
- Nonlinear PD regulation of the Quanser Ball and Beam system [Yu, 2009]
III. Robust Control: Gyroscopic motion control

Gyrosopes are used, now more than ever, in many devices including game controllers, aircraft guidance systems, spacecraft attitude systems, and so on. They are fundamentally used to measure the angular movement of a system relative to a fixed structure. In classic watercraft, for instance, the system is constantly being affected by disturbances (e.g., waves, wind) and the gyroscope maintaining its heading is crucial for proper navigation. These devices are therefore prime candidates for robust control.

In [Ruiz-Léon, M., and Henrion, 2002], representing the University of Guadalajara, Mexico, in collaboration with colleagues from the Centre National de la Recherche Scientifique, France, Czech Academy of Sciences, and the Czech Technical University, Prague, the authors develop controllers using $H_2$ and $H_\infty$ optimization techniques for a two-degree of freedom gyroscope system. The Quanser Gyro/Stable Platform is used to validate and compare control performance of each scheme. The Quanser Gyro/Stable Platform is an add-on module to the Quanser Rotary Servo Base Unit [SRV02]. The large inertial disk is mounted on a pivot that can rotate axially and its angle is measured using an encoder. The gyroscope module is mounted on the external gears of the Quanser SRV02 and its position is measured using the servo encoder. The servo sits on top of two rotating plates. When the top plate is rotated, the gyroscopic control should compensate and rotate the servo gear such that the heading of the disc is maintained.

The angle between the servo and the ground is, however, not known. It has to be estimated using the disc deflection angle and angle of the disc with respect to the servo. Simple estimation schemes and linear control work, but it may behave differently depending on the magnitude or type of disturbance and the unit may eventually experience drift. Optimization control can improve the robustness of the system.

The authors looked at different implementation schemes of $H_2$ and $H_\infty$ control but wanted to use the most practical method. They settled on a mixed sensitivity $H_2$ method that starts with a generalized plant and has a simple polynomial approach that allows the control to be designed using the MathWorks Polynomial Toolbox.

After selecting weighting functions $W_1(s)$, $W_2(s)$, $V_1(s)$, and $V_2(s)$, they determined a gain that successfully stabilized the gyroscope. They also noticed that selecting a larger sensitivity function, $S(s)$, caused the actual gyroscope to be more sensitive to perturbations, contrary to what was observed in simulation.

For the $H_\infty$ design, they chose a frequency-based method versus the more traditional state-space. The gyroscope system is already modeled using a transfer function representation, readily facilitating a frequency-based method. In optimization, a feedback gain $K$ is calculated that minimizes the $H_\infty$ norm and stabilizes the closed-loop system. The $H_\infty$ control performance was similar to the $H_2$ control. However, in this case it was found that if the sensitivity function was set very low the simulation would perform better.

In conclusion, both methods performed very well against step-like disturbances provided that the filter and parameters selection takes the characteristics of the physical system into account. This is also a prime example of how simulation and implementation results can differ significantly.

Other published papers on robust control that use Quanser equipment:

- Applying $H_2$ and $H_\infty$ control methodologies for vibration attenuations in flexible structures, tested on the Quanser Active Mass Damper system [Santos, Bueno, Marqui, and Lopes Jr, 2007].
- Robust nonlinear controller is designed using dynamic surface control for high position tracking performance on the Quanser Magnetic Levitation system [Yang, Miyazaki, Kanae, and Wada, 2004].
- Robust optimal model matching control design method is applied to the Quanser Rotary Flexible Link experiment [Popescu, Sendrescu, and Bobasu, 2008].
- Robust iterative learning control designed for the Thermo CRS 465 Robot through the open-architecture integration and RCP software provided by Quanser [Tayebi, Abdul, Zaremba, and Ye, 2008].
IV. Optimal Control: Model predictive control of fluid levels

Model predictive control (MPC) has gained popularity over the years in the chemical processing industry. MPC is computation-intensive, so it often cannot be implemented on embedded controllers and was used solely for slow systems. However, by modifying the algorithm, MPC has been successfully implemented on systems with faster dynamics than chemical processes. The authors in (Currie and Wilson, 2010), from the Auckland University of Technology, New Zealand, wanted to assess if MPC could be implemented on a low-cost embedded platform and used for autonomous underwater vehicles and UAV type applications.

MPC utilizes a constrained optimizer, which reduces down to a quadratic program (QP) for linear system estimation. One way to make it faster is to use a lookup table instead of QP – known as Parametric MPC. However, the authors found that this method has very short horizon times and is better suited for simpler models – not UAV type applications. They instead investigated a lightweight MPC control for systems less complex than industrial processes and that can be implemented on an embedded solution. By looking at five different QP protocols, the authors found that the infeasible interior point algorithm was the best choice to achieve at least 1 kHz sampling rate on an embedded target and obtain satisfactory tracking performance.

To test their controller, the authors chose the Quanser four-tank experiment. This an unstable, non-minimum phase MIMO system that is also nonlinear due to the square root relation between the tank outflow and pump voltage. The control challenge of this system provided a good benchmark before moving on to UAV-type devices. This quad-tank experiment is actually a combination of two Quanser Coupled Tanks devices. Each tank is fitted with a pressure sensor to measure the level of the liquid. The input and output flow between the pump and tanks is re-configurable and the flow rate can be changed by using different sized outflow orifices. In this case, involving the quad pump system, the authors want to control the level in two tanks using the two actuated pumps. Control constraints include the tank level capacity and the maximum pump voltage.

The full control is first tested using a PC with Rapid Control Prototyping software interfacing to the coupled tanks device through a DAQ. In initial tests, they found that the infeasible interior point algorithm struggled to find a feasible solution in less than 30 iterations with the imposed constraints. After some testing, the authors increased the prediction horizon and obtained satisfactory closed-loop response - all done using low sampling times. Being able to stabilize the system at low sampling rates becomes an important criterion when implementation is being performed on low-cost embedded hardware.

The control was then deployed on various embedded platforms: a PIC micro-controller, DSP chip, and two FPGAs. All these embedded solutions were suitable to control the sophisticated four-tank system and most of them were able to reach sampling rates of up to 1 kHz. Thus the authors have shown that embedded MPC is a feasible control solution that can be implemented on modest hardware and can be used to control challenging systems.

Other published papers on optimal control that use Quanser equipment:

- Nonlinear model predictive control implemented on Quanser 3 DOF Helicopter [Zhai, Nounou, Nounou, and Al-Hamidi, 2010].
- Linear model predictive control with complexity reduction, implemented on Quanser 3 DOF Helicopter [Johansen and A., 2002].
- Coupled building control using acceleration feedback method is tested on two joined Quanser Two-Floor Active Mass Damper systems [Christenson, Spencer Jr, Hori, and Seto, 2003].
- Comparing closed-loop results of Model Predictive control and Digital Linear Quadratic (LQR) control on the Quanser Rotary Flexible Link [Soimu, 2010].
- Application of a semi-discretization method to the stability analysis of PID control of linear systems with time delay, tested on the Quanser Rotary Flexible Joint experiment [Sheng and Sun, 2005].
- Generalizes and validates experimentally the applicability of a recently developed output-feedback sliding mode tracking controller based on a hybrid switching compensator on the Quanser Rotary Servo Base Unit [Nunes, Hsu, and Lizarralde, 2006].
V. Intelligent Control: Fuzzy logic control in space robotics

Flexible link robot arms in spacecraft pose major control challenges due to the requirement for light weight, fast response with minimal energy consumption, and vibration minimization. Neural networks have been proposed for such applications as they do not require dynamic modeling and are inherently adaptive. They can potentially handle modeling uncertainties common in the flexible structure. Fuzzy logic control is another option for such applications as well because it is computationally efficient, robust and couples easily with neural network-based learning algorithms. In this paper [Nikpay, Shoorehdeli, and Teshnehlab, 2011], the authors from the University Malaysia Pahang, design two different neuro-fuzzy (NF) controls and test them on Quanser Rotary Flexible Link system.

The Flexible Link is an add-on module to the Quanser Rotary Servo Base Unit [SRV02]. The flexible, aluminum link has a strain gage sensor to measure the deflection of the tip and it is mounted on the load gears of the motorized rotary servo. As the servo tracks a desired angle, the goal is to minimize the deflection of the link as well as any vibrations encountered. Due to the nature of this aerospace the application, the control must be also simple to implement and energy-efficient.

Two types of neuro-fuzzy (NF) controls are investigated: a PD-like NF controller and an importance-based NF controller. Both approaches utilize a Mamdani inference method. The rule base is altered in each approach to express the relationship between the different input variables. For both control schemes, the inputs that are used are the servo position, link tip deflection errors as well as the derivatives of those. Each approach prioritizes different variables in the system, which can affect the closed-loop performance.

The NF controls are trained using the error back propagation through plant (EBP-TP) method with an added emotional algorithm to help compensate for noise and disturbance, which are not dealt with using EBP-TP alone.

In simulation, both methods produce similar results when a fixed plant Jacobian vector is used for the emotional algorithm. When an adaptive Jacobian is used, the overshoot and settling time are improved in the response but the power consumption, i.e. motor voltage, increases. The decrease in overshoot and settling time was particularly better in the importance-based NF control.

When the different neuro-fuzzy controls were ran on the actual rotary flexible link hardware, the importance-based NF obtained better performance in terms of overshoot, settling time, and steady-state vibration. It also matched the simulation results better, which may be due to its ability to deal with uncertainties.

Other published papers on intelligent control that use Quanser equipment:

- Three types of controllers are designed - linear PID control, modern LQR control, and neural network control - and their performance when run on the Quanser Ball and Beam system is compared [Rahmat, Wahid, and Wahab, 2010].
- Takagi-Sugeno fuzzy controller with Adaptive Neuro-Fuzzy Inference System (ANFIS) architecture is used to stabilize the inverted pendulum on the Quanser Linear Inverted Pendulum experiment [Saifizul, Zainon, Osman, Azlan, and Ibrahim, 2006].
- Minimum time swing up of a rotary inverted pendulum using an iterative impulsive control is realized on the Quanser Rotary Servo Base Unit [Wang, Chen, and Fang, 2004].
VI. System Identification: Development of a low cost IMU for UAVs

In [Perez-D'Arpino, et al., 2011], the authors, from the Simon Bolivar University in Argentina, develop an inertial measurement unit (IMU) specifically for UAV applications. For typical UAV applications, the IMU must be able to handle fast dynamics, disturbances (e.g. vibrations due to propeller engines), and simultaneous movement in 6 DOF. In addition, the actual hardware must be lightweight and low-cost.

The authors use a Kalman-based sensor fusion attitude identification algorithm. The IMU board is separated into a sensor board and a data acquisition/processing board. Simultaneous sampling is performed by using a separate A/D converter (ADC) for each channel and prevents loss of orthogonality in the inertial measurements. They also use anti-aliasing filters that are tuned based on studies done with gyroscope and accelerometer readings on UAV-type devices, like scale helicopters. This can avoid high vibration interference in attitude estimation.

To verify the attitude estimates, the IMU board is mounted on the Quanser 2 DOF Helicopter. This is a bench top model of a standard helicopter with a main rotor and anti-torque tail rotor. The helicopter body is mounted on a pedestal through a two degree of freedom instrumented joint that allows it to rotate about the pitch and yaw axes. The position of these axes is measured using high-resolution encoders. The system is controlled through the PC using Rapid Control Prototyping software.

The authors were able to verify that the pitch and yaw angle estimates from their IMU matched the encoder-based angle measurements. They also showed how the Kalman filter pitch angle estimate was more accurate and less noisy than using raw accelerometer results without sensor fusion [i.e. from the tilt equations]. For the yaw angle, an additional sensor (e.g. compass) is needed to remove the drift in the estimate [estimate uses only gyroscope measurements, accelerometers cannot be used for yaw motion]. To simulate the addition of a compass sensor, they used the encoder-based yaw measurement from the helicopter. The results demonstrated how this improved the resulting IMU yaw estimates and that this additional sensor would be necessary before UAV testing. In addition, all these tests were performed with the IMU sensor board mounted near the propeller, replicating the operating conditions and disturbances involved on an actual UAV.

Final tests were then performed on a remote controlled, 6 DOF scale helicopter. This helicopter can move in free space and its position is acquired using infrared cameras. They authors conducted similar comparison tests with this platform but were also able to test how well the IMU estimated the roll angle. The estimates matched the actual measurements from the IR camera. In conclusion, the IMU prototype has the performance for UAV applications. The next IMU prototype will be redesigned to be lighter and include GPS and compass sensors.

Other published papers on system identification that use Quanser equipment:

- How to incorporate a cascade structure with two subsystems using different methods is investigated and tested on the Quanser Coupled Tanks [Hagg, Wahlberg, and Sandberg, 2010].
- On-line system parameter identification and state estimation evaluated on the Quanser Linear Inverted Pendulum [Park and Hong, 2005].
- Procedure for time variant system identification implemented on Quanser QNET HVAC system [Finca, Zglimbea, Greaban, and Marin, 2009].
Bibliography


