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Precision Control of a Slender High Payload 22 DoF Nuclear Robot System: TARM Re-ascending

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Abstract
The DEMO Remote Maintenance System (RMS) functional requirements represent a truly extreme environment. In the current design of the in-vessel RMS, blanket segment maintenance represents one of the most challenging tasks overall. As part of the JET (Joint European Torus) project, an ambitious 22 DoF transporter was created, the TARM (Telescopic Articulated Remote MAST). The TARM has been identified as a suitable test bed for the early development and verification of the control system and structural simulators. This paper outlines the development of the TARM into a multi-purpose test-rig for Precision Control of a Slender High Payload large DoF Nuclear Robot System.

Introduction

The DEMO Remote Maintenance System (RMS) functional requirements and working conditions are extremely demanding [1]. The operational complexity, very high payloads, elevated temperatures and gamma radiation, limited feedback and sensing, along with very tight working clearances, produce a mix that no present robotic technology can solve simultaneously.

In the current design of the in-vessel RMS, blanket segment maintenance represents one of the most challenging tasks overall. The weight of the segments can be as high as 80 tonnes [2, 3] with temperatures over 100 ^{0}C [4], contact dose levels up to 2kGy/h [4], and some level of magnetization of the Eurofer steel. The in-vessel handling of those massive components shall be achieved with clearances of just 20mm [2], with very limited feedback.

Within each torus segment, the blanket layer is split into five multi module segments (MMS): two in-board segments (IBS); and three out-board segments (OBS). Each MMS is extracted and replaced through the upper port, requiring it to be manipulated in-vessel and positioned below the port such that it may be lifted vertically. Given the layout of the MMS within the port, this results in the need for them to be extracted and replaced in a specific order; starting with the out-board MMS (central, then left and right), then the in-board MMS, one after the other. The most complex manipulation is for the first in-board segment extracted, as it must clear the remaining in-board segment as well as be translated outwards and downwards. The kinematic operations for each segment differ. A 40mm toroidal gap was left for the OB MMS, and 25 mm for the IB MMS, to facilitate extraction [4]. These blankets must be removed using the same manipulator and control system, namely the adaptive position control system (APCS). Thus, a test platform for Precision Control of flexible Slender High Payload manipulators is needed.

As part of the JET (Joint European Torus) project, an ambitious 22 DoF transporter was created – the TARM (Telescopic Articulated Remote MAST). This was designed to perform maintenance tasks outside the JET vacuum vessel. It features a large vertical telescopic mast with a vertical movement range of up to 11m, and a horizontal boom with 8 DoF. This is combined with a 6-tonne crane mounted on a rotational ring at the top of the mast. It also has the capability of mounting a Mascot manipulator both at the base of the vertical mast and on the end of the horizontal boom. The development of the JET programme and reduction in the expected radiation environment meant that TARM was never fully utilized, and eventually became used as a source for spares.

TARM has been identified as a suitable test bed for the early development of the control system, it has hence been transferred, restored and upgraded to allow it to be used as a development platform.

A software testing environment has been created in parallel to the restoration of TARM. This features a dynamic model to represent TARM. As the TARM restoration was completed, a thorough characterization programme was carried out to fully evaluate each joint, obtaining real data for friction and stiffness within each joint along with measurements for mass and centre of gravity. This model represents a validated digital twin of TARM, allowing initial control system development to be carried out with minimal risks and hence increasing confidence in software to be tested on TARM. This model can be further utilized by any other planned testing for TARM.

This paper outlines the development of the TARM into a multi-purpose test-rig for precision control of a slender high payload large DoF Nuclear Robot System.

TARM

Control System

Originally the TARM was designed to be used in the JET Torus Hall for ex-vessel maintenance, as well as the small possibility of inserting the boom through the port door for in-vessel operations. This meant the drive solution had to be radiation tolerant, resulting in the use of resolvers and tachos radially wired, along with the motors, on the end of large wiring looms fed down the boom and back through the vertical mast.

Figure 1: Components of the TARM.

It was decided the TARM upgrade does not have to be radiation tolerant as it will not have to carry out any operations in a radiation environment. This meant that the drive architecture could be redesigned to better suit the modular nature of the boom and the APCS requirement of reconfigurable kinematics. This modular redesign allows for greater flexibility from the control system, allowing for easier and less complicated deployment of control systems. It will also allow for the rapid addition of new components, such as sensors, without requiring major disruption. Whereas, if a sensor was added the original centralised design, the sensor would have to be retrofitted to fit the existing cabling or a new cable would have to be fitted at great cost and disruption. However, it is deemed with the advances in rad-hard components a rad-hard distributed control system will be plausible in the DEMO time-line [5].

Based on this work, a distributed drive architecture has been selected, in which the drives are placed down the length of the boom fed from a single DC bus. This greatly reduces the number of wires required down the boom, as well as placing the drives closer to the motors, reducing noise and EMF issues. The drives also take advantage of industry standard bus communications in the form of EtherCAT, allowing a single cable (down the boom and back again) to address every drive. The APCS required IO (resolvers, IMUs, load cells, and wireless microphones) will also connect to EtherCAT IO on a separate EtherCAT bus to share the traffic. The two EtherCAT buses will have their own EtherCAT Master connected to TARM control system to allow the data from each bus to be shared.

Similarly, the original control system of the TARM was not compatible with any of the new hardware and the operating system is no longer maintainable. The new control system is able to support the new hardware as well as accommodate changes to the configuration suitable for the *DEMO APCS Test Rig*. The RACE Control Systems and Software group has been developing a control system, known as CorteX, for several years which is designed to deal with exactly this challenge.

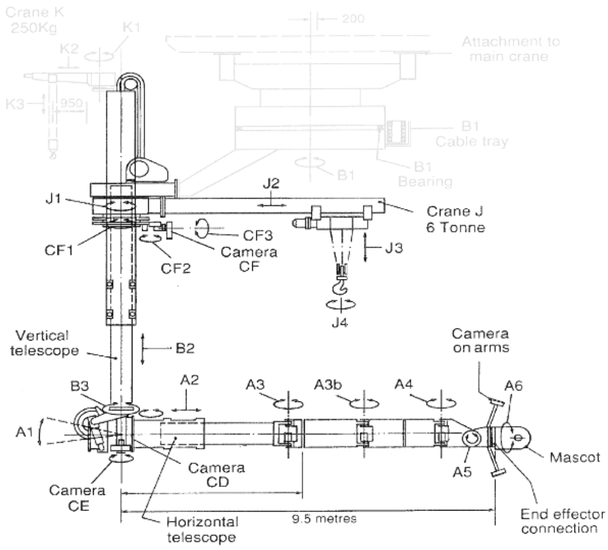

Figure 2: TARM with joint labelling.

CorteX is a dynamic, highly modular, generic and adaptable control system. It allows us to develop controls quickly and efficiently for an unlimited list of hardware, with the straightforward ability to modify and extend those controls to use different hardware and different control techniques. This functionality will allow APCS development to use different TARM configurations (with/without the addition) and different motor control techniques (such as competing back-driving) simply by changing a configuration file.

Application specific modules have been written for CorteX to allow it to integrate with the new TARM hardware, as well as control modules to allow conventional control of the TARM boom. These modules have been developed to satisfy the DEMO APCS Test Rig Requirement as well as general TARM integration. CorteX also has a GUI counterpart which provides an interface for users to command the control system. The CorteX control system uses an "Observe, Modify, Demand" structure - the world is observed by reading from sensors, which the controllers then use to calculate how they wish to modify the world, and finally these modifications are combined and sent to the hardware as a demand.

The model includes a placeholder for the *APCS Controllers* and their calculated modifications. This is where the custom controllers resulting from the APCS development will reside, allowing new control methods to be easily integrated and tested. There is also a placeholder for the A6 control chain, which will allow the APCS development team to experiment with different backlash compensation techniques to better control the A6 joint.

CorteX will finally host a series of experimental control systems, featuring adaptive model-free controllers [6], visual servo-ing techniques, and deep reinforcement learning control methods. Similarly, advanced sub-controller techniques will be tested, such as competing motor back-driving controller, controlling different backlash compensation techniques and neural-network based friction estimators [7].

Sensing

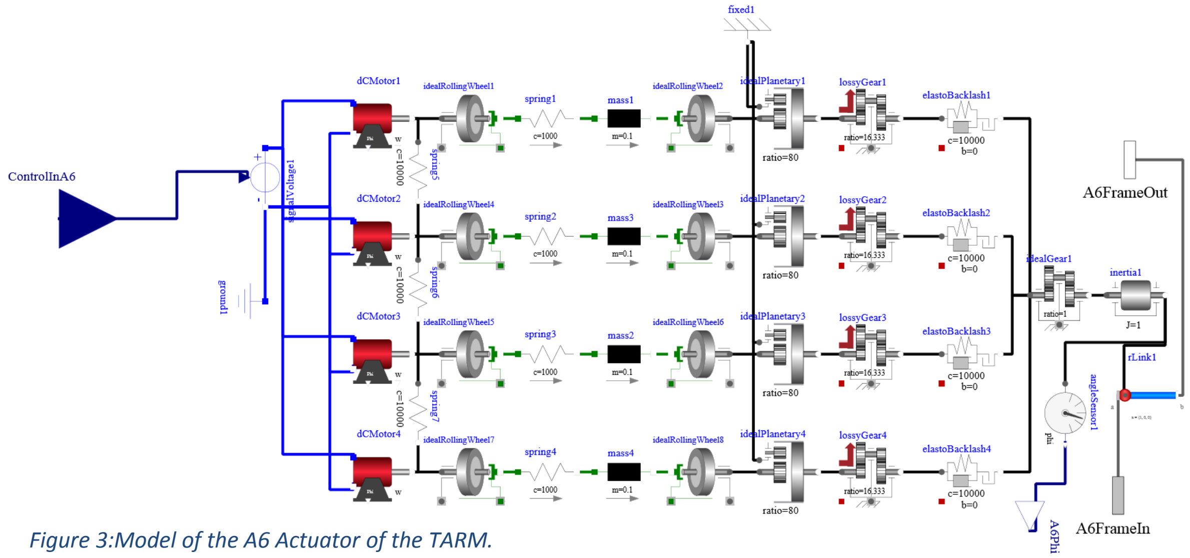

Figure 3:Model of the A6 Actuator of the TARM.

For testing purposes, a suite of sensors has been identified. For testing the effect of flexible joints on the test-rig, the rotation of both the motor and joint will be measured. It is necessary to measure the angular position and velocity of the joints and motors with an update rate equal to that of the motor drives. These measurements have a resolution of at least 0.2% of the range of the joint, and interface with CorteX. This facilitates the study of the highly non-linear effect of deformation on harmonic drives, planetary gears, and cycloid gears in complex arrangements. Similarly, motor torques are derived from current flow to the motors for all motors. Sensors have a bandwidth at least equal to the update rate of the motors (3kHz) to provide feedback information to the control system.

Each joint gearbox will require a separate solution for measuring torque due to the differences in the mechanical transmission systems. The worst case calculated gearbox dynamic torques for each joint are summarised in the Table 1. Any sensing solution must be able to detect torques at least up to the torque presented in the Table 1, with a resolution of at least 0.2% of the presented maximum.

Table 1: Torque at Joints.

Joint	**Peak Joint Static Torque [Nm]**	**Combined Rated (peak) Motor Torque [Nm]**	**Peak Joint Dynamic Torque (no payload) [Nm]**
A1	70701.1 Nm	2 x 2.65 = 5.3	3.186 kNm
A2	1930.16N/1612.07N (linear force)	2 x 1.27 = 2.54	22.24 kN (Linear force)
A3	2938.29 Nm	1 x (33.9) = 33.9	5.42 kNm
A3b	1231.05 Nm	2 x 2 = 4	5.47 kNm
A4	191.74 Nm	1 x (33.9) = 33.9	2.64 kNm
A5	306.1 Nm	6 x 0.247 = 1.482	27.32 kNm
A6	18.359 Nm	4 x (1.11) = 4.44	15.08 kNm

IMUs, containing 3DoF accelerometers and gyroscopes, are to be placed at multiple points along the beam, one for each joint. Cameras will be mounted on the TARM to observe the payload regarding a fixed position in the inertial frame. In addition, there is a camera mounted to a viewing arm which may be manoeuvred to change the angle of view. These cameras must have a frame rate of at least 60 fps and a latency of less than 10ms to allow for real time monitoring. These cameras will be controllable through CorteX, and hence will support appropriate protocols.

In addition, the camera system has been designed to be (optionally) mounted on a Tripod for external viewing of the boom arm and payload. The test rig has the capability to measure the acoustic noise in different components during operation. The test rig will have a freestanding RGB-D camera system and a freestanding 2D LiDAR system to measure deflections along the arm or on the payload. This is reconfigurable and should be able to detect significant multi-millimetre deflections. A 3D LiDAR system could be used to generate a point cloud of the boom from which positional information could be obtained. This would have the same requirements for resolution as the 2D LiDAR but would allow for measurements to be more robust.

Moreover, environmental cameras can be used for high frequency and high accuracy measurements for external verification of the control system and Structural Simulator.

Payloads

The TARM has been redesigned to be as adaptable as possible regarding payloads. The primary payloads that will be initialled investigated are:

- A passive payload, to simulate various lump mass on the end of the manipulator;
- An active payload, to simulate liquids and other deforming payloads on the end of the manipulator;
- A 6DOF robotic payload, to simulate the complex back forces resulting realistic operational tasks.

- A tele-robotic payload, to simulate the complex back forces resulting realistic tele-operational tasks.

The payload is connected in a modular fashion, as with the Control Systems, with the payloads controller decentralised to the payload. The decentralised payload controller is then connected to the rest of the system through EtherCAT and CorteX, allowing for modular distributed control. This flexibility allows reduction in complexity for the development of future components.

Discussion

A powerful platform for the development and verification of control systems and strucutral simulators for precision control of a slender high payload, highly flexible, large DoF, and high accuracy nuclear robot system has been presented. This platform provides a generic verifiable testing rig for a wide range of manipulator problems that are likely to be present in a number applications throughout the decommissioning and waste management field. As components grow in size and complexity and environments become less friendly to human entry, larger robotics will be needed. Moreover, as manipulators must deal with more complex tasks such as moving liquids, a test-rig will be needed. The test-rig presented provides a flexible platform for testing and resolving these issues. This paper presents some of the issues and considerations for design of similar test-rigs or final manipulators.

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