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MASCOT 6: Achieving High Dexterity Tele-manipulation with a Modern Architectural Design for Fusion Remote Maintenance

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The MASCOT system is a dexterous tele-manipulator robot which is well established and proven through thousands of successful hours of operation in remote reconfiguration of the Joint European Torus (JET) tokamak. The system is well suited to the types of complex remote maintenance tasks that will be found in fusion devices such as JET, ITER, and DEMO in the future. Over the past 3 years, a programme of work has been undertaken to upgrade the MASCOT system, which has been driven primarily by the need to replace obsolete components and improve reliability. The quality of the tele-manipulator system's performance can be defined in terms of transparency and fidelity, which can be further attributed to system parameters such as bandwidth, reflected inertia, friction components, current sensitivity, and transmission smoothness. As the required performance is extremely demanding, significant analysis and optimisation has been required in order to approach a suitable solution. We present the state of the MASCOT Version 6 technology including, for the first time, an overview of the system design and features as well as the design and results of performance characterisation simulations and experiments. The state of the programme, and plans for future work will also be presented.

I. INTRODUCTION

Mascot is a two-armed master-slave tele-manipulator robot with seven degrees of freedom per arm. This system is routinely used for remote maintenance and reconfiguration of the JET tokamak experimental fusion reactor at Culham, UK [1]. Its role is to maintain the inside of the reactor vessel without the need for manned entry, and it has played a key role in vital experimental configuration [2] and diagnostic calibration [3] tasks. The master and slave movements are linked by a force-reflecting servo-system, giving the operator haptic feedback when doing remote work. The slave is typically attached to an articulated, snaking robotic boom, which transports it to the work area.

The master is typically located in a control room from which the operator-controlled input actions provide the motion that the slave will replicate. Mascot version 4.5 [4] is currently in use at the Joint European Torus (JET) experimental nuclear fusion facility. The Mascot 6 project, funded by the JET Operating Contract (JOC), was initiated to address reliability and availability issues arising as a result of obsolete technologies. In particular, the Mascot actuators are based around obsolete 2-phase AC induction motors, which are to be replaced with actuators based on modern, commercial off-the-shelf (COTS) Permanent Magnet Synchronous Motors (PMSMs). As a consequence of its highly coupled, monolithic design, combined with years of modifications the entire Mascot 4.5 control system, including servo amplifiers, controllers, software and HMI required redesign.

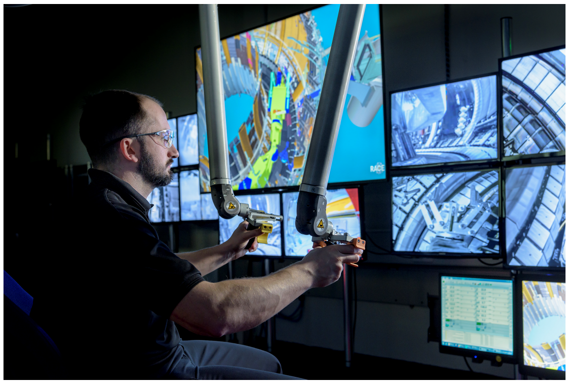

FIG. 1: The mascot master being used to replace components within the JET tokamak.

This has required substantial re-engineering, and as such has presented an opportunity for modernisation and improvement to the system.

Due to the absence of detailed specification documentation, combined with highly challenging performance requirements, significant work has been carried out in order to characterize existing system performance, as well as evaluating the comparative performance of prototype systems.

In order to achieve this, a number of experimental procedures were developed, and two dedicated test rigs were designed and constructed.

This paper presents the current state of the design, along with details of the test processes that have been used to characterize existing and prototype systems, along with results.

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II. SYSTEM ARCHITECTURE

A full architectural design has been carried out which includes structural, behavioural, and physical definitions of the system, at the top-level (full system) as well as drilling down into internals of key subsystems such as the new control hardware.

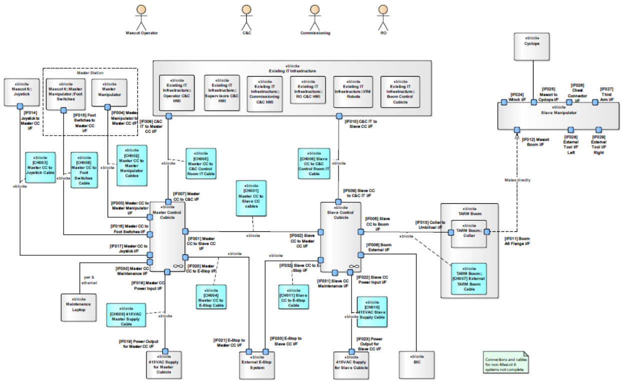

FIG. 2: Mascot 6 top-level design (physical view).

Although the requirement is primarily related to achieving equivalent performance with the existing system, the adoption of modern good-practices and constraints of available technologies have led to a substantial deviation from the previous system design. In particular, the significant differences between the requirements of master and slave actuators have led to a divergence of design concepts between the two, providing opportunities for performance improvements and cost reduction. Use of modern, readily available motor technology (Permanent Magnet Synchronous Motors) has introduced a new, and significant challenge which must be overcome.

The software system is based on VxWorks and Linux , and implemented using the RACE CorteX control system framework, thus allowing for significant flexibility in capabilities and collaboration with other devices and software. Control algorithms and computer-assisted teleoperations include those present in version 4 [5], with some additions.

Other key aspects of the system architecture include the use of an EtherCAT bus for distribution of controlled devices. This is extended by fiber link between the master and slave controllers, allowing for a high-speed, real-time, communication system that is able to distribute the teleoperation system over significant distances.

Building on the existing safety systems, a Master operator safety scheme is implemented in accordance with ISO/TS 15066 on collaborative robotics [6].

III. MODELLING & SIMULATION

A simplified single joint bilateral system has been mathematically modelled and a variety of simulations and analysis performed on the model including comparisons between the Mascot 4.5 and Mascot 6 designs and parameter sensitivity. Deriving the equations of motion yields the equation below:

$$\begin{aligned}&\ddot{\theta}_1(J_{ma}+n_{arm}^2(J_{mac}+J_{mmr}n_{masterGB}^2))\\&+B_{cs}n_{arm}^2(\dot{\theta}_1\\&-\dot{\theta}_2)+B_{cs}B_{mvf}\dot{\theta}_1\\&+K_{cs}n_{arm}^2(\theta_1-\theta_2)=0\end{aligned}$$

$$\begin{aligned}&\ddot{\theta}_2(J_{sa}+n_{arm}^2(J_{sac}+J_{smr}n_{slaveGB}^2))\\&-n_{control}(B_{cs}n_{arm}^2(\dot{\theta}_1-\dot{\theta}_2)\\&+B_{mvf}\dot{\theta}_1+K_{cs}n_{arm}^2(\theta_1-\theta_2))=0\end{aligned}$$

Where $n_{control}$ is the configurable torque multiplication factor in the control system, θ_1 and θ_2 are the master and slave positions respectively, J_{mac} and J_{sac} are the master and slave actuator inertias, J_{ma} and J_{sa} are the master and slave arm inertias, $n_{masterGB}$ and $n_{slaveGB}$ are the master and slave gear ratios, n_{arm} is the arm transmission ratio, K_{cs} and B_{cs} are the control system stiffness and damping parameters, B_{mvf} is the master viscous friction coefficient.

Transforming into a state space form yields the matrices below. B is altered as needed depending on the test.

$$\begin{bmatrix}\ddot{\theta}_1\\\dot{\theta}_1\\\ddot{\theta}_2\\\dot{\theta}_2\end{bmatrix}=A\begin{bmatrix}\dot{\theta}_1\\\theta_1\\\dot{\theta}_2\\\theta_2\end{bmatrix}+BU$$

where

$$A=\begin{bmatrix}\frac{B_{cs}n_{arm}^2-B_{mvf}}{J_master} & 1 & \frac{B_{cs}n_{arm}^2n_{control}}{J_slave} & 0\\\frac{-K_{cs}n_{arm}^2}{J_master} & 0 & \frac{K_{cs}n_{arm}^2n_{control}}{J_slave} & 0\\\frac{B_{cs}n_{arm}^2}{J_master} & 0 & -\frac{B_{cs}n_{arm}^2n_{control}-B_{svf}}{J_slave} & 1\\\frac{K_{cs}n_{arm}^2}{J_master} & 0 & -\frac{K_{cs}n_{arm}^2n_{control}}{J_slave} & 0\end{bmatrix}^T$$

and

$$\begin{aligned}J_{master}&=J_{ma}+n_{arm}^2(J_{mac}+J_{mmr}n_{masterGB}^2)\\J_{slave}&=J_{sa}+n_{arm}^2(J_{sac}+J_{smr}n_{slaveGB}^2)\end{aligned}$$

TABLE I: Results from master step-input simulations

Performance Measure	Mascot 4	Mascot 6 w/ Mascot 4 tuning	Mascot 6
Kcs (Nm/rad)	180	180	180
Bcs Nm/(rad/s)	0.75	0.75	0.4
Overshoot (%)	35.5712	10.7618	35.7687
Rise time (s)	0.0194	0. 0320	0.0236
Phase Margin (deg)	52.4	111	52.2
Bandwidth (hz)	13.97	7.24	11.46

TABLE II: Results from slave step-input simulations

Performance Measure	Mascot 4	Mascot 6 w/ master tuning	Mascot 6
Kcs (Nm/rad)	180	180	180
Bcs Nm/(rad/s)	0.75	0.4	0.7
Overshoot (%)	38.6162	60.6771	37.1023
Rise time (s)	0.0175	0.0105	0.0129
Phase Margin (deg)	48.3	25.6	50.3
Bandwidth (hz)	15.34	24.67	20.85

TABLE III: Results from slave moment pulse input

Performance Measure	Mascot 4	Mascot 6 w/ master tuning	Mascot 6
Kcs (Nm/rad)	180	180	180
Bcs Nm/(rad/s)	0.75	0.4	0.7
Peak amplitude (Nm)	58.3	51.5	44.6
Peak time (s)	0.0182	0.0222	0.0242
Phase Margin (deg)	44.4	20.2	37.7
Bandwidth (hz)	15.58	12.75	11.63

The parameters used in tests were taken from records of MASCOT components, combined with measured values taken from the existing system . The control system parameters for Mascot 4 were derived based on system overshoot requirements, tuning Mascot 6 to the same overshoot parameters allowed a comparison of its ability to obtain similar performance.

Three main sets of simulations were conducted in order to characterize the performance resulting from proposed new hardware designs, as well as constraints on the design arising from complex interactions in performance characteristics. The first two involved creating a step position input at each of the Master and Slave ends, and measuring the resulting system response. The final simulation involved providing a torque pulse to the slave end.

In the first set of simulations, the V6 control parameters were tuned until the resulting performance closely matched the V4 performance.

The results from conducted parameter sensitivity simulations gave indications as to the effect of parameter variations, however, in practice, more than one parameter would change at once and the control system parameters would likely be changed to compensate. The key findings from these tests were that the small and linear effect that the viscous friction values have on the dynamic performance and the slave force multiplier damping the system due to the high sensitivity of the system to the control system damping value. The impact of time delay was as expected with an increase in delay increasing overshoot, however, there was little impact of delay in the 0.001 – 0.002s range in which the system will be operating. The second simulation used the same model as before, except the position input was inserted into the slave state.

The mascot 4 system's relatively equal master and slave inertia means that gains for both the master and slave can be the same (and therefore closest to a real spring/damper) while this is not true for Mascot 6. The inertia of the slave will limit the overall system performance if we are to tune the slave to master gains to match the master gains. The final set of simulations involved the placement of a torque pulse into the slave side of the system. The master inertia was set to 1e100 kg.m2 to keep the master relatively fixed in lieu of an operator. The tuning was kept the same as in the previous simulations.

Although the slave position step input tests showed better performance in all areas for Mascot 6, the torque impulse response is significantly worse, as can be seen from the reduced phase margin and bandwidth in Table III. This is likely due to the increased inertia of the Mascot 6 slave that is required to be accelerated by the impulse.

During this process, parameter sensitivity tests were also conducted, which showed, as expected, a reduction in performance as the inertia increased with the motor inertia having the largest impact due to the gear box. The slave force multiplier changes demonstrated that as the amount of force required from the master is reduced, so is the response to a slave torque input.

These simulation results, along with prototype test results have been used to inform a further design iteration.

IV. PERFORMANCE CHARACTERISATION

Detailed prototypes of master and slave actuation units have been produced, based on component selection carried out through previous trials and selection processes. Due to the high difficulty and complexity associated with achieving compliance with performance requirements, simplified prototype actuators were built and tested in order to physically measure performance and optimize design choices to meet the requirement.

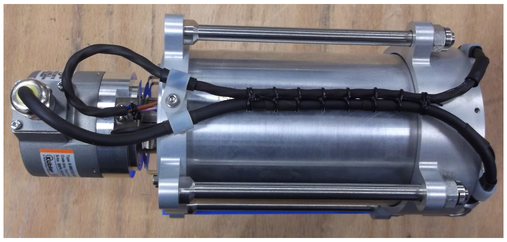

FIG. 3: Prototype Master actuator constructed for performance evaluation.

Prototype actuators have been constructed to be as closely representative to the final product as reasonably practical in order to identify unforeseen design issues.

Prototype actuator performance was measured using dedicated test facilities. The first, known as the Actuator Test Rig is designed for comprehensive measurement of performance of rotary components and systems.

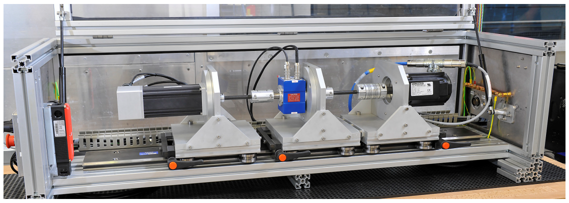

FIG. 4: The actuator test rig used for performance measurements during the development process.

This test facility was used both to characterize individual components (e.g. motors, encoders) during the design and selection phase in order to provide performance measures not reported by the manufacturer, and subsequently to measure performance of the overall actuation system including software , drive electronics, and mechanical components. Results are reported below.

Results are presented for four test cases, which characterize the key mechanical properties of the actuator assemblies, specifically static friction, dynamic friction, inertia perceived at the actuator output shaft, and overall torque ripple in the system.

Tests were conducted on the component or system either through back-driving using an external load motor, active forward-driving with a load, or a combination of both. Both dynamic or static loads could be applied to the system depending on the requirements of the test. Torque and velocity data between the component under test and the load was captured using an external measurement system including a high-resolution, calibrated torque transducer. Test data was then post-processed analysed using scripts developed for the GNU OCTAVE environment.

The full test and characterization programme was conducted using an agile-sprint methodology encompassing performance testing combined with troubleshooting and enhancing the system.

V. RESULTS

Results are presented in Table IV and show generally acceptable performance for the Master actuator, and unacceptable performance with the slave actuator in terms of the basic mechanical properties. Characterisation results for both Mascot 6 and Mascot 4 are compared against the Mascot 6 requirement, derived from original Mascot specifications.

It is worth noting that the most significant non-compliance of the master (static friction) was further investigated and found to be the result of magnetic reluctance variations (cogging torque) in the motor. Once compensated for in software, the static friction was re-measured and meets the required level. Hence, the present prototype actuator is in-line with the specified performance levels.

The slave actuator performance is significantly below requirements and is currently undergoing a full design iteration in order to address shortfalls in-line with test and simulation results.

VI. DISCUSSION & FUTURE WORK

The Mascot 6 project involves a major upgrade of the existing JET telemanipulator robot facility. The present status of the project has been presented, along with significant simulation and test results showing evaluation of the first design iteration. Initial results show that whilst the master systems is

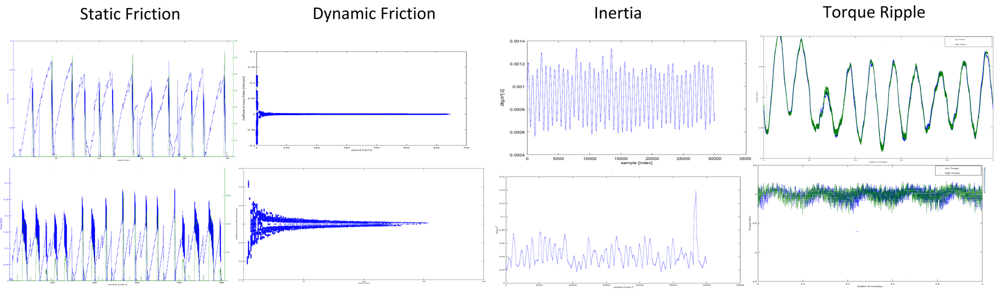

FIG. 5: Example outputs following the 8 reported tests. Top row shows master actuator performance. Bottom row show the corresponding outputs for the slave.

performing adequately, the slave system is performing below requirements.

TABLE IV: Results from actuator physical trials.

	M6 Requirement	**Mascot 4.0**	**Mascot 6.0**
Master: Static Friction (Nm)	0.027	0.600 (+492%)	0.095 (+251%)
Master: Dynamic Friction (Nm)	0.0540	No Data	0.000480 (-1%)
Master: Dynamic Friction (Average Coefficient) Nm/rpm	0.00064	0.000038	0.000057 (-91%)
Master: Average Inertia $kg.m^{-2}$	0.0052	0.018953 (+72%)	0.000922 (-82%)
Master: Torque Ripple (Nm P-P)	0.05	0.0	0.112
Slave: Static Friction (Nm)	Not Defined	0.0989	0.179 (+81%)
Slave: Dynamic Friction (Average Coefficient, Nm/rpm)	Not Defined	0.000119	0.000262 (+120%)
Slave: Inertia ($kg.m^2$)	Not Defined	0.023476	0.0420 (+79%)
Slave: Torque Ripple (Nm P-P)	Not Defined	0.0	0.639

Informed by test results, insights obtained during the test process, and detailed simulations, a final design iteration is to be undertaken, progressing the design towards final, compliant design. Final prototypes will next be re-tested in the same manner as presented, as well as the production of a full-scale, 2-armed 7 degree of freedom manipulator for full-system validation and alpha-testing.

VII. ACKNOWLEDGEMENTS

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