# Novel distributed real-time control system for a target motion simulator

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## ABSTRACT

Traditionally, control systems are designed in a single computer with discrete analog and digital signals to the power amplifiers or other components. Emerging real-time bus technologies open the possibility to modularize such a control system and simplify the system design. It offers more flexibility and better maintainability. The system control can be distributed between state-of-the-art servo drives, digital IO, sensors and the control computer. All the components are connected via a real-time network which communicates the data deterministically. An implementation with this new approach is shown and explained with a large scale 10 degrees-of-freedom motion simulator.

**Keywords:** Target Motion Simulator, Flight Motion Simulator, HWIL, EtherCAT, DTMS, TMS, FMS

## 1. INTRODUCTION

Target Motion Simulators (TMS) and Flight Motion Simulators (FMS) are used to simulate tracking and target engagement scenarios for guided missiles. The goal of the simulation is to develop and test the missile control system and to validate the system performance in a laboratory environment. The laboratory environment allows for exact reproducibility of the test environment at lower costs.

The TMS simulates the motion of a target. Typical targets include vehicles and buildings or fast moving objects like airplanes or attacking missiles. The FMS simulates the rotary movements of the missile that wants to hit the simulated target. The missile typically is able to detect infrared (IR) or radio frequency (RF) scenarios; therefore the TMS is equipped to simulate the signature of an IR or RF target. To exclude external influences and RF reflections, both the TMS and FMS simulators are usually placed inside an anechoic chamber.

The FMS is a three axis motion simulator. All three axes are orthogonal to each other, perform rotational movements and intersect in a single point. The most inner axis is the roll axis and typically has unlimited rotation. The middle axis pitch and outer axis yaw axes are limited to a certain angle of movement, for example +/- 60degrees.

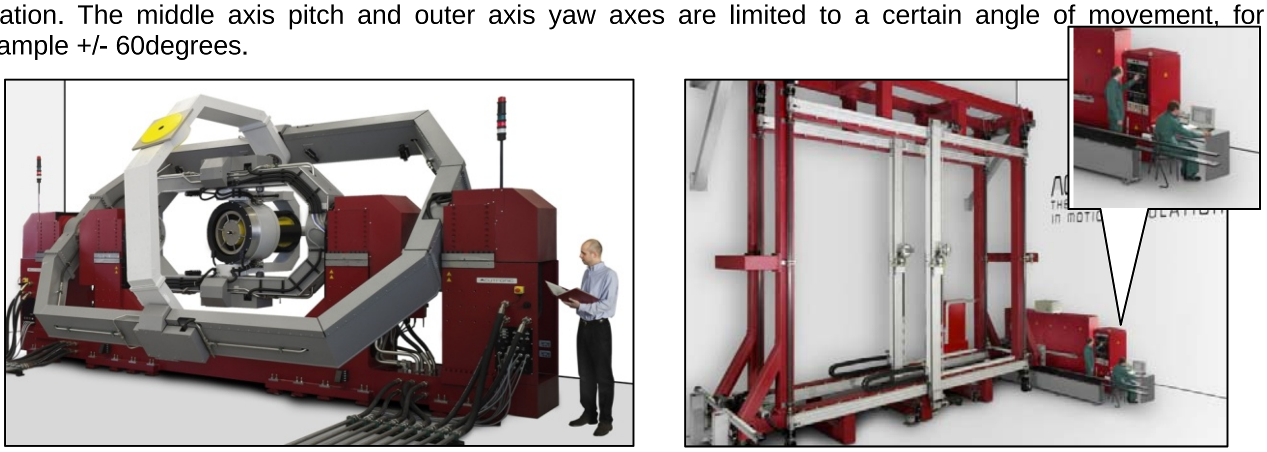

Figure 1: Five axis Hardware-in-the-loop simulator with *near field* TMS is depicted on the left. A DTMS for *far field* target simulation is shown on the right. Observe the persons in the pictures for relative sizes.

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To combine the FMS with a suitable TMS three basic principles are commonly used. The first is the *near field* TMS, usually used for IR targets. In this case the distance between the missile seeker head and the target is not critical, because the IR target is a collimated beam. The near field TMS (Figure 1) consists of azimuth and elevation rotational axes around the FMS. If the seeker is directly aligned with the target, then the elevation axis of the TMS is collinear with the pitch axis of the FMS. For yaw and azimuth the same relation is true. The distance between the missile seeker head and the target is in the order of 1m.

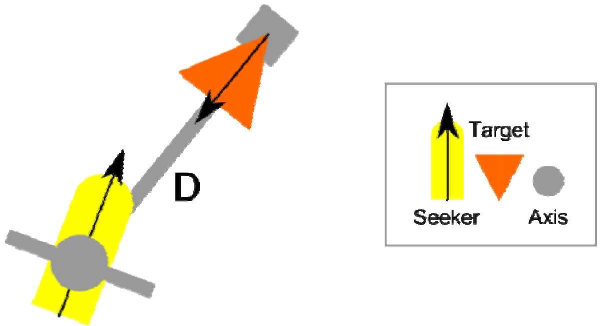


Figure 2: Target and seeker axis, connected with a fixed gimballed system: near field TMS configuration.

The other two options are called *far field* target motion simulators. They are configured as a two axes linear or curvilinear X-Y positioning systems. The distance between the target and the missile seeker head depends on the wavelength of the RF targets or source and can be many meters long.

Curved frames (Figure 3) have the advantage that the target is always pointing back to the missile seeker head, given their mechanical design. The distance between the FMS's center of rotation and the TMS is fixed and identical with the radius of the curved frame.

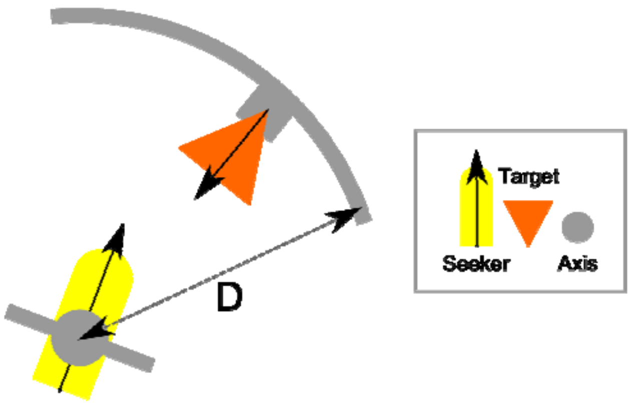


Figure 3: Curved frame TMS configuration. Distance to the target, D is constant.

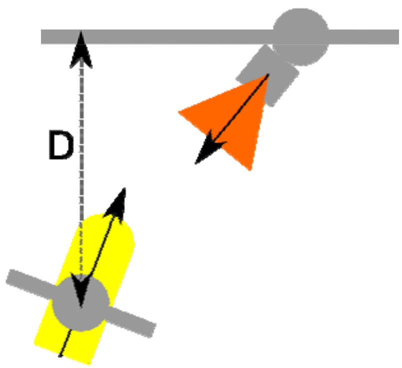


Figure 4: Flat frame TMS. Distance to the target, D, can be varied.

A flat frame TMS (Figure 4) offers more flexibility, as the distance between missile seeker head and target can be varied. A three axis gimballed system is mounted on the linear rail. The additional axes ensure that the target constantly points back towards the missile seeker head. The pointing is coordinated by software and can therefore be adapted to different distances, whereas the curved frame has a fixed radius given their mechanical design. The flat frame TMS has a more simple mechanical structure and facilitates the integration of multiple targets.

## 2. SYSTEM DESIGN

This paper explains the novel approach of the control architecture on an example of a Dual Target Motion Simulator (DTMS) manufactured by ACUTRONIC. A DTMS has two flat frame target motion simulators behind each other. The following section gives a short introduction about the DTMS setup to give a better understanding of the overall design.

### 2.1 Electro-Mechanical setup

The TMS consists of three main assemblies (see Figure 5): (a) the horizontal rail assemblies (X direction), (b) the vertical rail assemblies (Y direction) and (c) the gimballed payload mount. Two horizontal rail assemblies, one on top and one on the bottom, span over ±7.5m and guide the X-axis movement. On each X rail assembly a carriage (d), equipped with motor, gear head and pinion is installed, that runs on the track. The upper and the lower carriages are connected directly to the vertical rail assembly.

The vertical rail assembly spans over ±5m. A carriage on the vertical rail assembly, moving in Y direction, is driven through a belt by two brushless DC motors (e), one at each end. The motors are directly coupled to the belt shaft. An electromechanical brake holds the axis against gravity when the servo loop is not active.

Mounted on the carriage of the vertical rail is the three axes gimballed payload mount. Two of the axes are used to maintain the pointing angle towards the centre of rotation of the FMS by tilting vertically or horizontally. The third axis is used to roll the payload around its own axis. Customer target hardware of up to 15kg can be incorporated on the payload mount.

The DTMS comprises of two linear and three rotational axes for each TMS which totals to 10 degrees-of-freedom.

The latest generation servo drives are used to ensure high performance dynamics. To determine the exact absolute position of the axes, additional feedback devices are mounted on the drive side. Fully digital linear absolute encoders are mounted directly on the vertical and horizontal rail assembly. The top and bottom carriage move independently and have no mechanical drive shaft between them. They are synchronized through software to ensure a parallel horizontal movement.

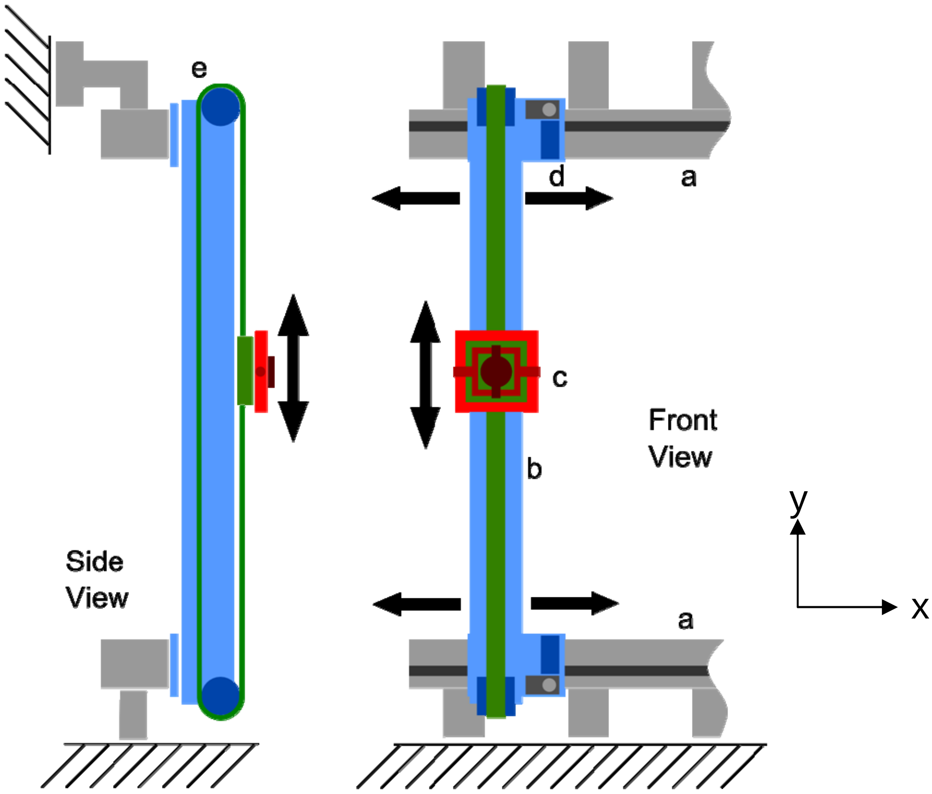


Figure 5: Side view and front view of the TMS. For simplicity a single target.

### 2.2 Safety

A set of safety related measures protect people and the machine itself in the occurrence of a fault. To ensure people safety the system can only be operated within a closed and locked anechoic chamber.

System synchronization between different motors, e.g., the lower and the upper X rail assembly motors, is realized through a real-time Ethernet and backed up with an advanced safety circuit. Additional optical devices monitor the alignment of the two carriages and report faults to the safety hardware.

Independent watchdog relays report the outage of any of the involved computer hardware and command an immediate system shutdown. Different levels of axis shut down procedures are implemented, ranging from fast stop algorithms to immediate power cut-off.

### 2.3 Customer interface

The DTMS is a major part of an overall synthetic testing environment designed by the end-user himself. This environment typically comprises target motion simulators, flight motion simulator, target hardware, e.g., radar antennas, radar seeker head, flight model computer, scene generation computer, control and data acquisition hardware.

Customer interfaces to the control architecture give direct access to all control parameters of the motion simulators (DTMS as well as FMS). For every calculation frame position, rate and acceleration can be commanded.

State-of-the-art algorithms inside the controller also accept commands with any fraction of the controller real-time operating system sampling rate or with reduced state vectors, e.g., only position and rate commands. Time skewing algorithms are designed for smooth operation of the system and simplify the commanding process. Plausibility checking of the individual commanded system states is performed either by the control system or ensured by the customer.

# 3. REAL-TIME CONTROL SYSTEM ARCHITECTURES

When designing a control system for a motion simulator, the basic components such as controller, drive, sensors and interfaces have to be evaluated. The challenge is to select the component which fulfills the needed specification and have the matching interface for communication.

## 3.1 Traditional approach

Traditionally the interface between components was done via analog signals. A single wire analog connection was used for each signal that had to be transmitted in each direction. Depending on the device, this resulted in many connections between devices as often more than one signal has to be exchanged such as data and status, drive- or enable commands.

Traditionally the controller was the center of the system, interfacing to all the devices individually to exchange information. As a result bundles with wiring had to be connected and this often over longer distance.

The advantage of the analog signal path is that it is very fast and deterministic. It is also universal as no protocol is involved. The disadvantage of using such an approach is becoming more obvious in large and distributed systems. As such signal degradation over long distance, noise pickup or ground loops are a few of the problems that can occur. And of course a complex and costly wiring work can result.

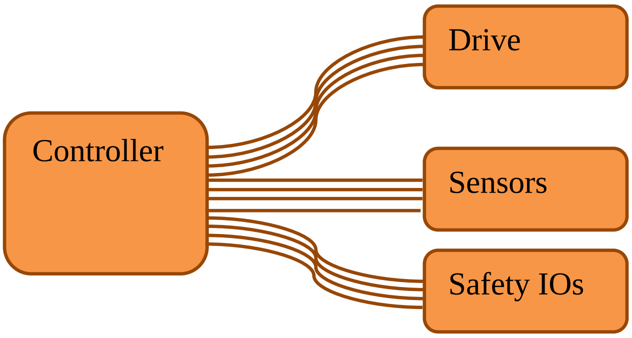


Figure 6: Traditionally connected system with individual connecting wires.

## 3.2 Novel approach

In the last few years several new fieldbus technologies have emerged which allow fast, deterministic communication between the controller and the associated peripherals and can be used for both real-time and non-real-time data transfers. As more and more device manufacturers incorporate these buses in their products, the selection of sensors, drives and other IOs becomes larger.

In a system designed with fieldbus architecture, such as EtherCAT®[1], a bus connects all the devices in series such as drives, sensors, and IO peripherals. Real-time data such as position information or drive commands can be exchanged as well as non Real-time data such as status and error words. There is only one connection and no individual wires have to be connected between the devices. This drastically reduces and simplifies the wiring of the system and increases the amount of information that can be exchanged through the bus.

A Controller normally handles the communication between the different devices. Some of the fieldbuses, such as EtherCAT, allow for synchronizing devices, so they all work on the same clock. They can even be individually corrected to compensate for additional delays or offsets.

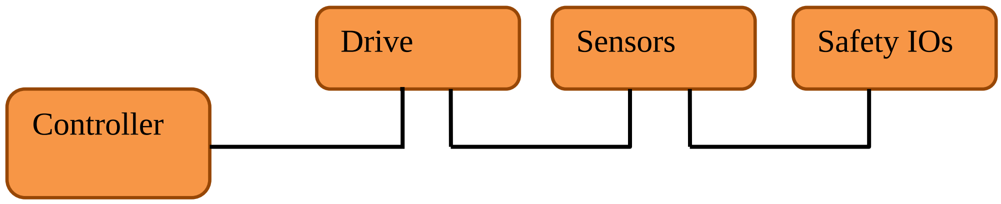


Figure 7: System with a single fieldbus connection.

### 3.3 EtherCAT

EtherCAT® is an open, non-proprietary, high performance Ethernet interconnect bus. Its strength lies in possible short cycle times (< 100µs) and low jitter (< 1µs). It is based on the Ethernet cabling and uses the basic Ethernet protocol. Other than standard Ethernet, where individual frames are sent to each targeted node which are then interpreted and processed, EtherCAT packs the messages for all the devices into one frame. Each device reads and inserts its data into this frame while it passes through the device. This reduces the number of frames that have to be sent and increases the determinism as the frame continuous to pass through the network without significantly being delayed. Normally the entire network can be addressed by one frame.

Hardware wise, EtherCAT uses the standard Ethernet hardware such as cables, connectors or switches.

### 3.4 Control topologies

Fieldbuses are one of the advancements in the industry. More intelligent drives and devices are another improvement. Nowadays servo drives have changed from being only a “voltage-current converter” to include control loops, filters, look-up tables and other control components. Also the new fieldbuses are being incorporated which allow them to be connected to a fieldbus network and exchange command data as well as feedback or status information with the controller in charge.

As an example two possible architectures are shown on how such a control topology could be conceived (see Figures 8 and 9). Each controller is realized using a set of nested control loops. The most inner loop typically is the torque or current control loop; it is realized directly on the servo drive hardware. A commutation sensor that determines the rotor position of the torquer is connected directly to the servo drive.

One possibility (Figure 8) is to close the position and rate loop on the control computer by reading the position and rate feedback from the drive. This requires a more advanced control software on the control computer as the compensation is mainly done on the control computer. On the other hand it allows tuning the behavior of the control system to a finer degree by adding more or advanced control components than is available in the drive.

Another possible solution is to close the position and rate loop on the drive using the built in control capabilities. This simplifies the software in the control computer but limits the tuning possibilities to the available features in the drive.

The system characteristics are generally modeled by a state observer which is running at the same frame rate as the control system and can be implemented in the control computer or servo drive. It estimates position, rate and acceleration of the servo axis. The model matching error of the real and the estimated position is used by the observer compensator to improve the observer tracking behavior.

The rate and the position compensation loops can be closed using standard second order filter elements. At least one of them typically has integrating behavior to ensure zero steady-state errors. Finally the system can be fine tuned using loop shaping feed-forward techniques. Look-up tables (LUT) on the control computer or drive can allow for compensation of ripple-torque effects of the motors and/or mechanical mounting errors of the axes.

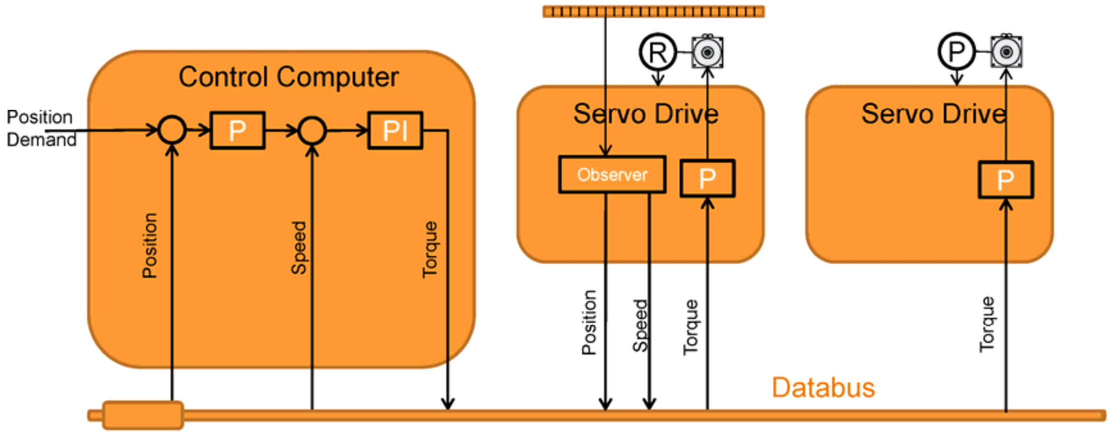


Figure 8: Position, rate and torque loops all closed in the control computer.

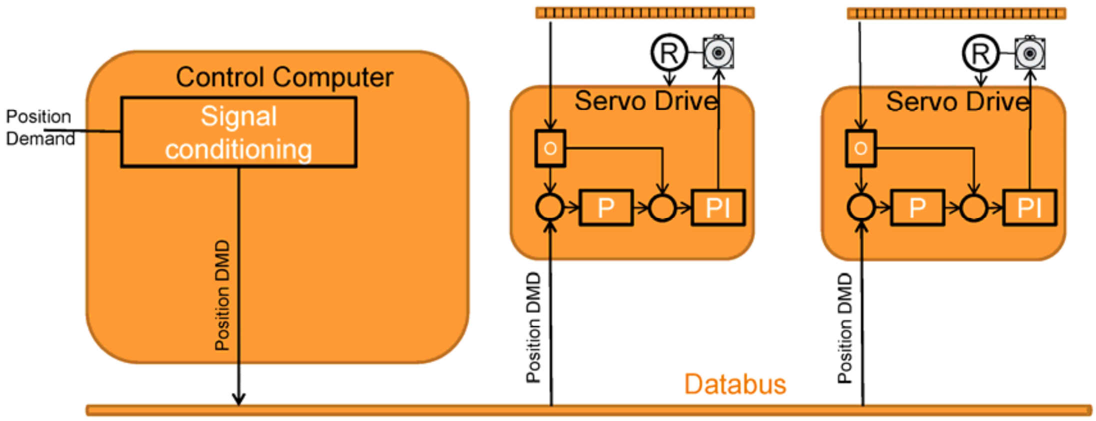


Figure 9: Position, rate and torque loops closed in the individual servo drives.

The distribution of the loops between the control computer and the drive can be defined depending on the drive configuration, compensation possibilities and other design requirements.

### 3.5 DTMS control system

The control system techniques described above are used to set the architectures for the DTMS.

To control the motion simulator a distributed real-time control system has been designed. The various control tasks are split between different components of the system, using the available intelligence of all components in an optimized way. Communication between components is realised using EtherCAT.

A key component is a supervisory control computer based on PXI architecture hardware. It acts as the master of the EtherCAT network and coordinates all the movements and safety tasks of a target motion simulator. Absolute position feedback is fed back to the control computer to feed the state observer to close the position control loop. Coordinate transformation between the X and Y positions and the tilt angles of the gimballed payload mount are also calculated here.

Seven intelligent servo drives per TMS, all connected to the EtherCAT bus, handle the high-bandwidth current loop directly on the drive hardware. In some cases further control tasks are also deployed on the servo drive, for instances a rate observer and a rate feedback loop. Safety functions and surveillance of operation is handled by both the servo drive hardware and the control computer.

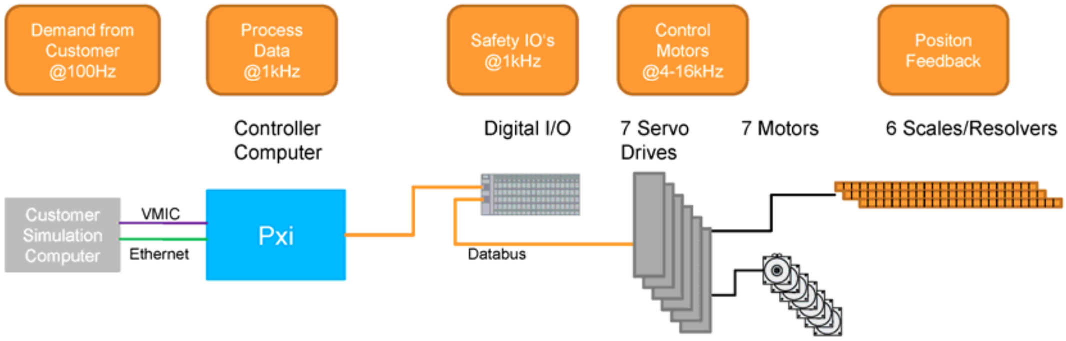


Figure 10: DTMS architecture.

Another important task of the control computer is to organize the communication to the customer host computer. Typically the end user commands and controls the DTMS from his own hardware in the HWIL simulation environment. A VMIC[2] reflective memory interface is installed for this reason. The customer can use the standard ACUTROL®[3] Command Language (ACL) features to configure and command the DTMS simulator.

## 4. PERFORMANCE AND RESULTS

### 4.1 Position and rate measurement

To demonstrate the position and rate performance the TMS was driven from the leftmost position at -3m to the rightmost position at +3m with acceleration of 10m/s$^2$ and a rate of 4m/s (Figure 11). The commanded position and rate are very accurately tracked by the control system of the TMS which leads to a very smooth movement without overshoot and oscillations.

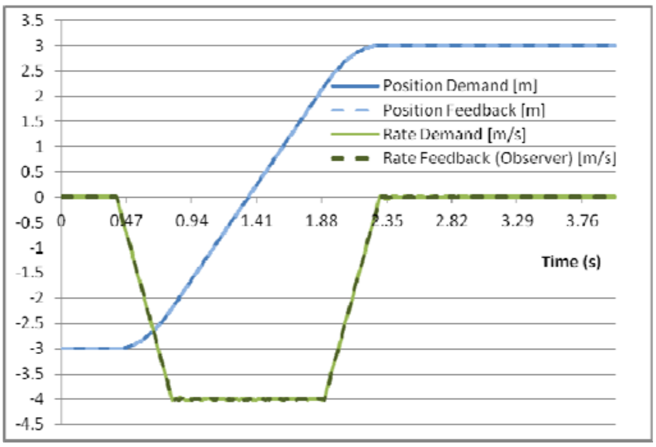


Figure 11: Position and rate profile during measurement.

### 4.2 Pointing performance

The DTMS receives position, rate and acceleration or a subset of it for the targets from the customer host computer as they are seen from the FMS. Depending on the distance between the target and the FMS, the commands are converted into the linear motion of the X and Y rail assemblies and corresponding angular movements of the gimballed payload mount.

The pointing performance therefore is an ideal measure to identify the combined static and also dynamic performance of the system. The coordinate transformation and all servo loops of the corresponding axes and the look-up tables were operational at the same time.

The static and dynamic pointing performance was measured with a laser which was mounted perpendicular on the payload platform of the DTMS. Figure 12 shows the area in which the pointing stayed during static and dynamic movement. The target was at a distance of about 20m from the FMS. The pointing performance requirements were to remain within a radius of 100mm for both X and Y positions; this is clearly achieved.

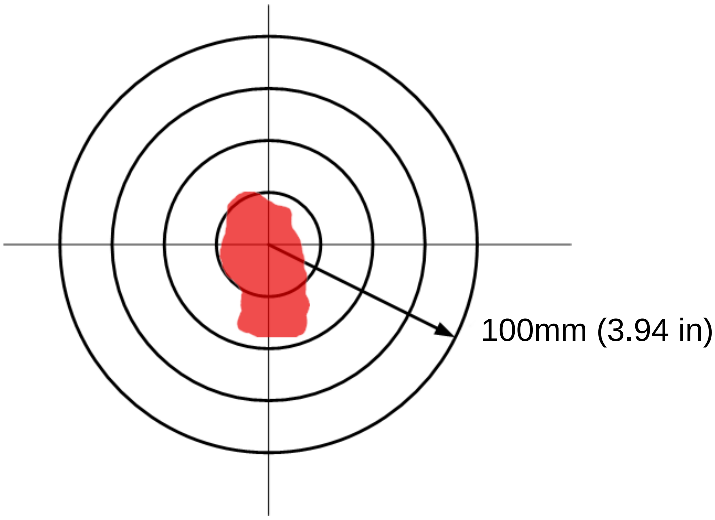


Figure 12: Pointing results are well within the 100mm specification.

## 5. SUMMARY

EtherCAT and other real-time buses allow designing a very flexible and distributed system. Wiring becomes easier, more flexible and cost effective. It allows using a distributed architecture where the device can be located closer to the data source without losing the real-time data availability which is necessary for such a control system. Device manufacturers have realized this as well and are incorporating fieldbus technology into their products. Care must be taken when selecting the correct bus as there are several different real-time bus systems on the market which all have their advantages and disadvantages.

EtherCAT proves to be a good and robust solution with deterministic real-time capabilities. It is employed successfully in dual-target motion simulators with 10 degrees-of-freedom and eight devices per simulator all, connected together via EtherCAT.

## REFERENCES

[1] EtherCAT Technology Group: www.ethercat.org
[2] VMIC is manufactured by GE Fanuc
[3] ACUTROL® is the state-of-the-art motion controller of ACUTRONIC: www.acutronic.com