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An Innovative Driving Simulator: Robocoaster

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ABSTRACT – This paper presents a new approach utilizing an industrial robot as an interactive motion simulator platform, to take advantage of both a highly flexible workspace and considerably lower costs due to mass production of the basic mechanics.

Driving simulators have been used for testing and validation for decades. They range from simple low-cost simulators with a fixed base to very complex and expensive ones which are hexapod-based with six degrees of freedom. The presented, innovative approach is a robot-based motion simulator combining the advantages of high motion flexibility and reasonable costs. The serial configuration of the robot mechanics provides a considerable larger workspace than a classical hexapod-based motion simulator, allowing tilt angles of more than ± 90 degrees. Hence, this serial configuration also introduces some difficulties concerning the path-planning of the simulator cell because of the more complex workspace and the existence of singularities in the workspace (configurations causing loss of degrees of freedom). The usage of standard path-planning algorithms like the classical washout-filter, only considering constraints in the Cartesian space, can lead to reference trajectories beyond the dynamical possibilities of the robot mechanics.

The paper will focus on the development of a new path-planning algorithm for robot-based simulators that can handle these problems. In combination with a visualisation system and a pilot seat, the industrial robot can be used as a comparably low-priced motion simulator e.g. for the test of vehicle dynamics. Additionally, the evaluation of the algorithm under real test conditions and comparison with the simulation results will be demonstrated.

TECHNICAL PAPER - The range of motion simulator kinematics spreads from trivial fixed-based simulators (no kinematic) to highly redundant and complex simulator kinematics like the DESDEMONA (1) motion simulator (both centrifugal and gimbal mounted pilot cell). In general, with increasing mechanical complexity of the simulator configuration, the costs of the simulator and the mathematical complexity of the control algorithms are also rising.

Industrial robots are the productive backbone of automated facilities since their introduction in the 1950's. Actual robot systems can handle loads up to 1000 kg (2) over ranges of 3 meters. Because of the mass-production of industrial robots, these are considerably cheaper than the specialized mechanics of most motion simulator systems.

Since 2003 KUKA GmbH company has been distributing a modified KUKA 500/1 robot, the so called KUKA Robocoaster. This system is a fun ride, approved for use with two passengers. The passengers are moved along a pre-defined trajectory which must not exceed limited accelerations.

Besides the fun factor of a carnival ride, the DLR Institute of Robotics and Mechatronics presented a non-interactive motion simulator at the AUTOMATICA 2004, based on a Robocoaster equipped with a projection dome (3). This combination was used for several motion simulations, like a Martian valley flight or a rollercoaster and avalanche simulation. In every case, the trajectories of the robot were pre-planned in order to meet the requirements of the simulated motions. Actual research efforts target the on-line path-planning of the simulation, allowing an interactive simulation experience controlled by a pilot.

Currently, the following simulation scenarios are focused:

- Driving Simulation
- Flight Simulation (including overhead flight manoeuvres)
- Sport simulation (e.g. skiing)
- Telepresence (e.g. drone control)

HARDWARE

For the Robocoaster, a modified KUKA KR500/1 TÜV (Figure 1 – right) is used as base mechanics with six actuated axes. Unlike the standard industrial robot, the Robocoaster has mechanical emergency stops, reducing the maximal possible acceleration for the passenger to 4.5 g in the case of a hardware crash. The maximum payload of this model is 430 kg, allowing maximum accelerations of the simulator cell of up to 1.8 g (configuration dependent). In the standard version, as provided by KUKA, the Robocoaster supports two passengers sitting side by side in two seats mounted at the robot flange.
The actual variant of the seat modified by the DLR adds two carbon fibre domes mounted on the retaining brackets of the seats (see Figure 1 – left). Each dome contains a visualization system (TFT display), a sound system and a ventilation system for the generation of an air flow simulation. An emergency shut-off button is located between the two seats, so both passengers can stop the simulation process at any time.
Unfortunately, the actual design of the chair does not allow much movement of the pilot’s arms, so for an interactive simulation with realistic controls like steering wheels a further redesign of the KUKA standard chair is inevitable.

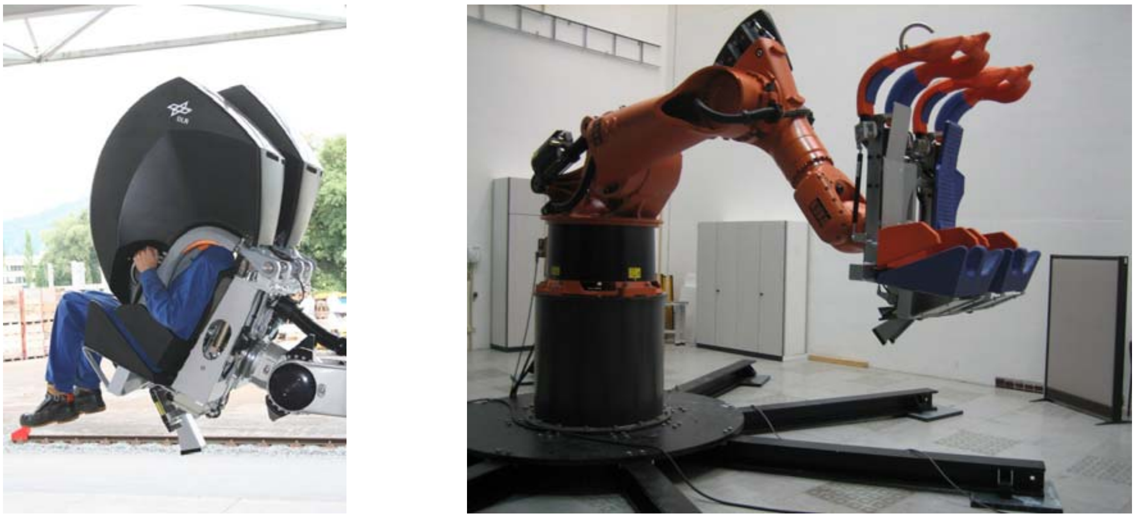

Figure 1 – Seat with fibre domes (left) and complete robot without domes (right)

OVERVIEW OF THE ROBOT MOTION SIMULATOR CONTROL COMPONENTS

The complete simulator control system consists of the components shown in Figure 2.

The **simulation** provides the physical environment for the motion simulation and contains the car or aircraft models.

Washout – Filters generate the motion cues mapping the large scale movement of the simulated vehicle into a restricted workspace. Hence, this workspace is not the exact workspace of the robot, so the

path-planning generates trajectories considering both the mechanical and dynamical constraints of the robot. These trajectories are calculated as a solution of a local optimization problem and follow the desired paths from the washout filtering, if possible.

The **robot-control** checks the calculated trajectories for their feasibility and stops the robot in case of any failure or trajectory errors.

From the simulation data, the visual environment for the pilot is generated by the **visualisation** system.

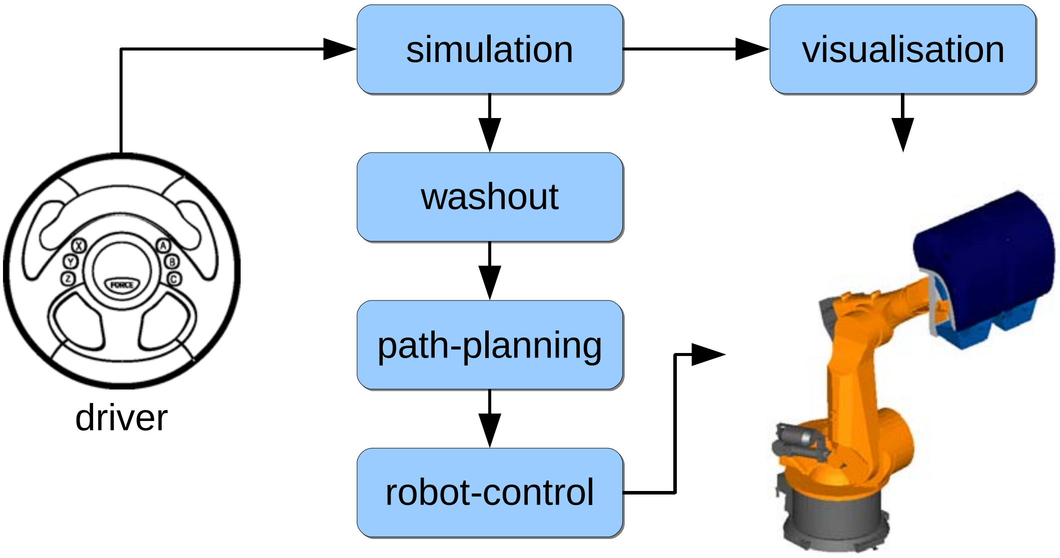

Figure 2 – Overview of the simulation control

A PATH-PLANNING ALGORITHM FOR A ROBOT-BASED MOTION SIMULATOR

For motion simulators, the path-planning algorithms are crucial for both realism of the motion-simulation and security of the pilot. While the classical hexapod has a homogenous workspace without singularities, the workspace of an industrial robot is more complicated. With workspace geometry in the shape of a spherical shell and several kinematic singularities within this workspace, additional mathematical precautions must be taken, in order to avoid infeasible movement commands.

Hexapod motion simulators use the unique hexapod inverse kinematics to directly calculate the necessary actuator commands. This is possible, because of the homogenous workspace of a hexapod kinematics.

For a robot-based motion simulator this procedure would introduce some severe problems: The workspace of the robot is more complex than the simple half-sphere geometry of the hexapods' workspace. Every joint of the robot must be constrained, so the hardware stops can not be reached during simulation progress. Furthermore, the movability of the robot depends on the actual configuration of the robot. Figure 3 shows an example of a singular configuration, where cell movements towards the robot base are impossible.

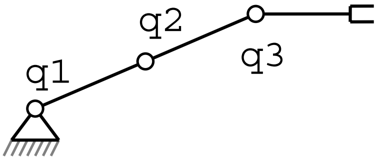

Figure 3 – Draft of a three axes robot in a singular configuration.

LOCAL OPTIMIZATION INSTEAD OF INVERSE KINEMATIC

Because of the problem described above, an additional control layer between the washout filter and the robot-control is necessary. This layer consists of a local optimization algorithm that aims to minimize the error between the desired cell movements calculated by the washout filter and the actual movement of the simulator cell. If the desired trajectory can be reproduced within the robot dynamic constraints, the solution of the optimization is equivalent to the inverse kinematics of the robot. In cases where the desired movement of the cell is beyond the dynamic possibilities of the robot actuators, a position or orientation error will occur. This error is minimal in terms of the robot operating at its physical limit.

The formulation of the inverse kinematics as an optimization problem has the advantage that mechanical and dynamical constraints can be taken into consideration as inequality constraints. In addition, single robot joints can be braked separately if their current position is near the hardware stops. Figure 4 shows the optimization problem in detail.

The matrix **A** contains the multi-objective, linearly formulated optimization problem for minimizing both orientation and position error. Equality and inequality constraints are linearly formulated in **E** and **G**. The regression vectors of the quadratic optimization are defined in $\underline{b}$, $\underline{f}$ and $\underline{h}$. The optimization process results in modification of the robot joint angles $\Delta\underline{q}$ in order to meet the limited robot workspace.

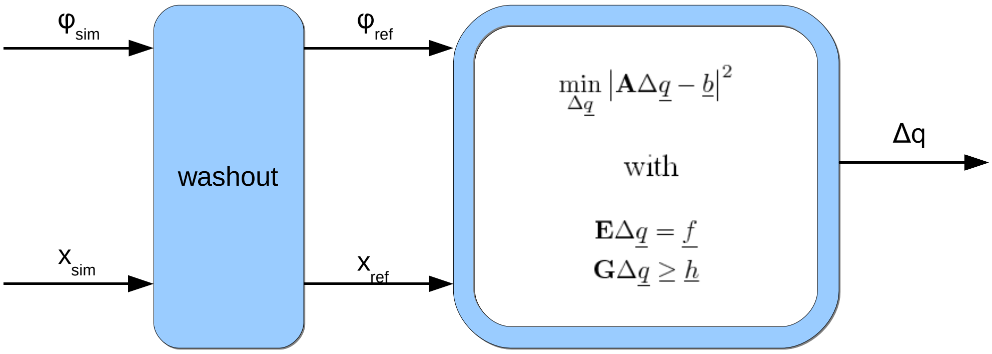

Figure 4 – Path-planning as an optimization problem

OVERHEAD FLIGHT MANOEUVRES

The movability of the Robocoaster axes 4 and 6, which can rotate unconstrained without any hardware stops (see Figure 4), allows simulation manoeuvres not possible with conventional hexapod systems. Imaginable scenarios are rollover situations in car simulations, rollers and loopings in flight simulations or disorientation scenarios for pilot training. Consequently, such extended movability opens new fields of application for motion simulation.

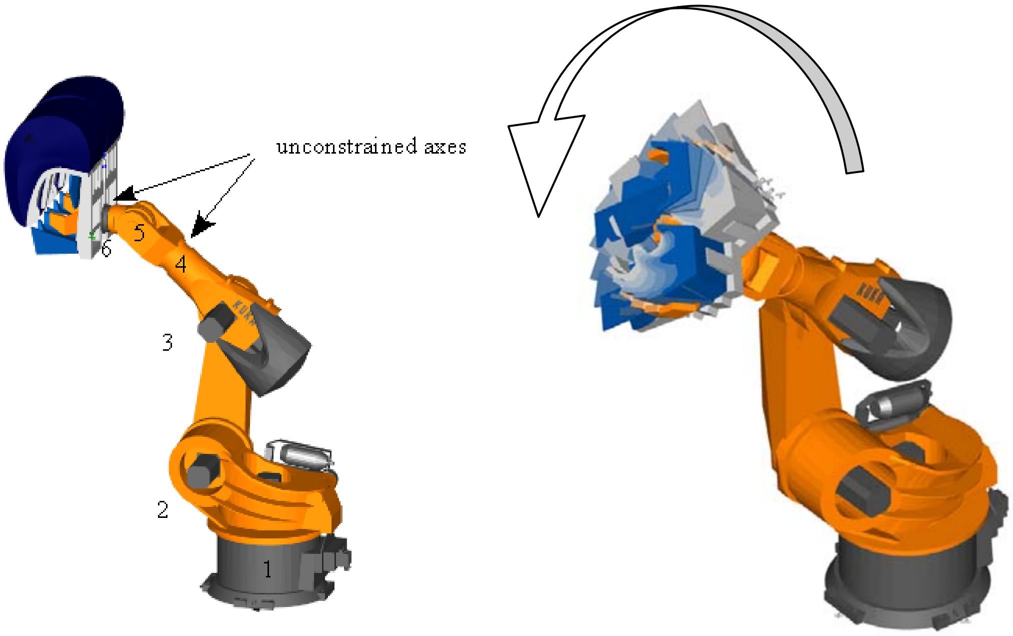

Figure 5 - Axes of the robot (left) and rollover manoeuvre of the simulator cell (right)

SIMULATION RESULTS

For validation of the control architecture, several simulations have been done. Figure 6 shows some selected diagrams of the simulation results. In the simulated scenario, a sports car completed a run on a racing track (Salzburg-ring - Austria), passing several curves and experiencing acceleration and braking manoeuvres. The two upper diagrams in figure 6 show the translatory accelerations in X- and Y-direction, comparing the desired acceleration (dashed line) reference resulting from the motion cueing algorithm and the acceleration provided by the robot’s mechanic (solid line). The lower left diagram shows the acceleration error between reference and robot coordinate system while the lower right diagram shows the orientation error between these two coordinate systems.

The discrepancy between the reference and robot acceleration (upper left diagram) occurs, since the maximum torque limits of robot actuators are reached. The acceleration and orientation error can be reduced by either slowing down the motion cueing filters or by increasing the robot motors’ torque. Hence, the resulting trajectory is locally optimal concerning the robot’s dynamic constraints.

For validation of the real pilot acceleration, an acceleration sensor system has been mounted on the pilot chair. This allows the measurement of the resulting pilot acceleration during a simulation run. Figure 7 shows the comparison between reference acceleration (dashed line) and measured pilot acceleration (solid line) for the three axes. The scenario in this simulation run was a double-bend with following braking manoeuvre. The difference between simulated and real acceleration is considerably small and should not be noticeable for the passengers.

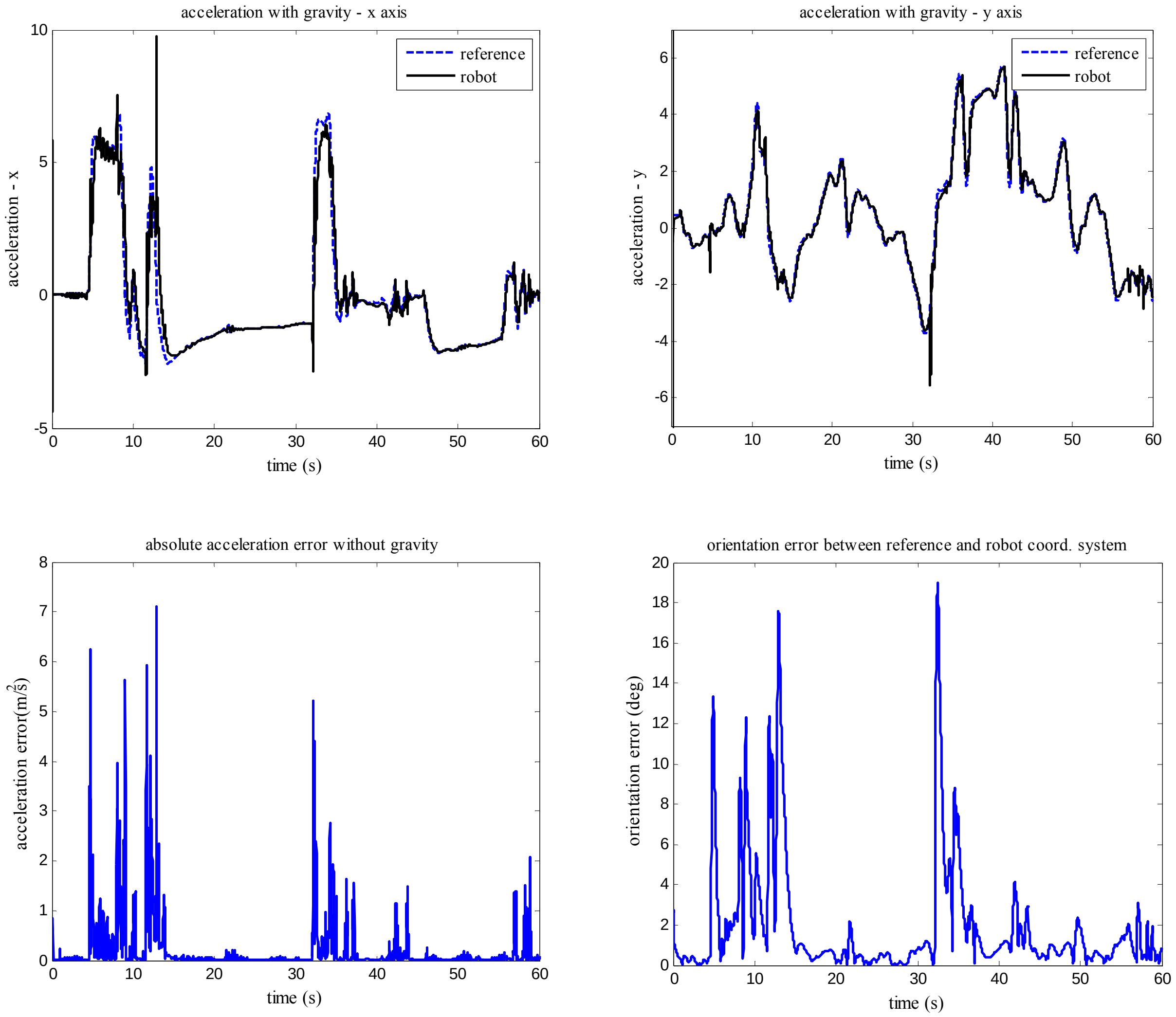

Figure 6 - Simulation results – above: accelerations of reference (dashed) and robot coord.-system (solid). Below: acceleration and orientation error between reference and robot coord.-system.

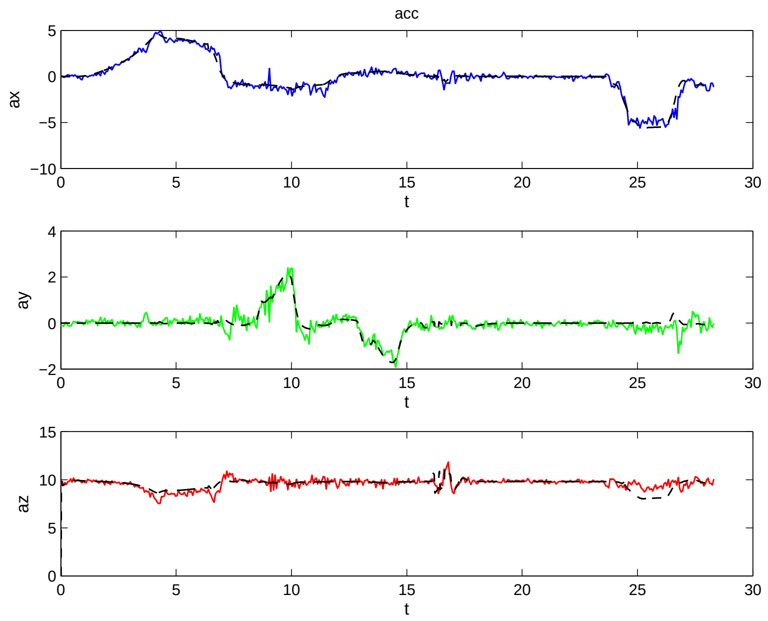

Figure 7 – Measured and reference robot accelerations in x-, y- and z-direction

CONCLUSION AND OUTLOOK

An innovative type of motion simulator based on serial robot kinematics and its functionality have been presented. The enhancement of the path-planning algorithms first presented in (4) and its validation with on-line applications like driving simulations have been shown proving the feasibility of this approach. Future development of the path-planning algorithm will focus on aircraft simulation with roll manoeuvres. Furthermore, modifications like combining pre-planned trajectories with interactive controlled simulations in order to enhance simulation experience will be focus of research.

The modularity of the combination of motion cueing and additional optimization path-planning allows the adaption of the simulator to several applications such as driving, flight or other motion simulations. Further modifications on the kinematic model will also allow the adaption of the path-planning algorithm to other motion simulators based on serial kinematics.

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