Opening the Door to New Sensor-Based Robot Applications — The Reflexxes Motion Libraries

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***Abstract*— This paper introduces the Reflexxes Motion Libraries and describes, how they open doors for next generation robot motion controllers. When robots become capable to perform sensor-guided and sensor-guarded motions, there is no predefined path anymore, and motions have to be calculated on-line, that is, during the motion. The Reflexxes Motion Libraries calculate jerk-limited motions within one control cycle only (typically $1\,ms$ or less). This way, robots can *instantaneously* react to *unforeseen* sensor events, which opens the door to a huge number of new robot capabilities and fundamentally new motion control features. For instance: unforeseen switchings of coordinate frames, unforeseen switchings of control state spaces, deterministic and instantaneous reactions to sensor signals, safe and stable reactions to sensor failures, simple visual servo control, and stable switched-system control. All these features are important for the execution of sensor-based robot motions and to realize new applications as will be outlined in this paper.**

I. Introduction

The *Reflexxes Motion Libraries* are designed to achieve new opportunities in sensor-based robot motion control opening the door to new applications, safe human-robot interaction, and advanced robot motion capabilities. The three key features of these libraries are:

(1) Robot motions can be calculated from arbitrary initial states of motion (i.e., during any motion).

(2) New motions are calculated within one low-level control cycle (typically within one millisecond or less).

(3) The interface is very simple and clear, such that it can easily be integrated in existing systems.

The libraries presented here are the outcome of a long-term research project of the robotics research groups at Braunschweig University of Technology [1] and Stanford University [2]. Based on these former works, the Reflexxes Company [3] now works on technology transfer projects to bring these new concepts widely into practice and to contribute to the future advancement of robotic systems. First major robot manufacturers are already using the fully documented and tested software libraries in their products.

This communication paper outlines the new control features and robot motion capabilities that become possible now. Furthermore, it describes different types of on-line trajectory generation (OTG) algorithms that are contained in the *Reflexxes Motion Libraries*.

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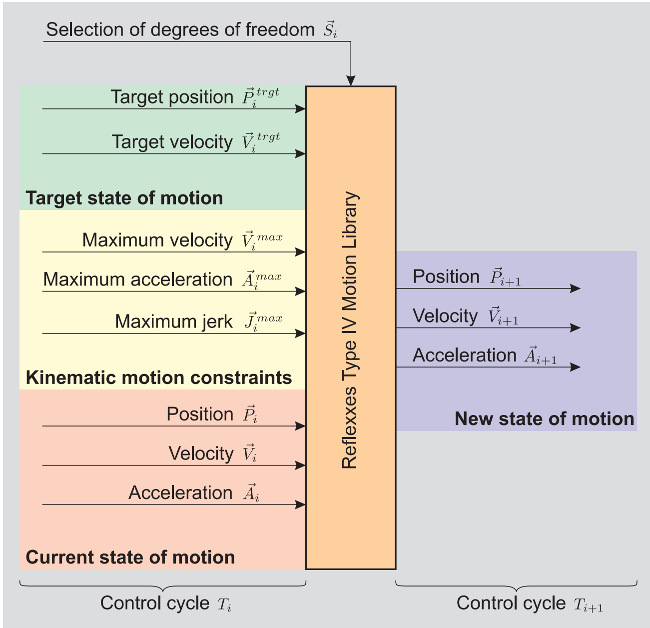

Fig. 1. The interface of all *Reflexxes Motion Libraries* is very simple and can easily be integrated into existing systems. Based on the **current state of motion** and the **kinematic motion constraints**, a **new state of motion** is calculated with lies exactly on the time-optimal trajectory to reach the desired **target state of motion**. All input values can change arbitrarily based on sensor signals and even discontinuously, and a steady jerk-limited motion trajectory is always *guaranteed* at the output.

II. New Robot Motion Control Features

Based on the OTG framework, the following new robot motion control features can be realized with the *Reflexxes Motion Libraries*:

A. Unforeseen switchings of coordinate frames
B. Unforeseen switchings of control state spaces
C. Deterministic, instantaneous reactions to sensor signals
D. Safe and stable reactions to sensor failures
E. Simple visual servo control
F. Stable switched-system control

All these features let robots *instantaneously* react to *unforeseen* events and enable new opportunities for sensor-based robot motion control — and thus: open the door to a wide range of new robot applications.

The Basic Concept

A number of former works [4]–[6] introduced the basic framework of on-line trajectory generation algorithms, whose interface is illustrated in Fig. 1. Given an arbitrary initial

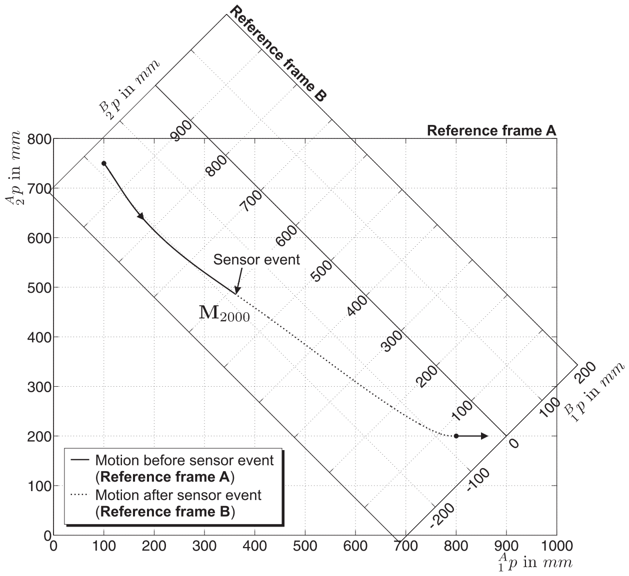

Fig. 2. XY-plot of a two-DOF *path*, whose trajectory is executed w.r.t. reference frame A (solid line). Right after the indicated sensor event (dotted line), frame B acts as reference frame for the motion controller.

state of motion, kinematic motion constraints, and a desired target state of motion consisting of a position and a target velocity vector, a new state of motion is calculated for the current control cycle. This state of motion lies exactly on the time-optimal trajectory to reach the desired target state. The calculation is so fast that the resulting values can be used as set-points for lower-level controllers within the same control cycle, such that instantaneous deterministic reactive motions are possible.

A. Unforeseen Switchings of Reference Frames

As motion set-points can be generated within one control cycle, it becomes — for the first time — possible to switch the reference coordinates instantaneously at unforeseen instants while a jerk-limited trajectory is always guaranteed, and some degrees of freedom may even be controlled by closed-loop controllers (e.g., force/torque or visual servo control). This is very useful for tasks, for which the reference frame of a motion is not known beforehand or is sensor-dependant. To give a simple illustrative example, Fig. 2 shows the planar path of a two-degree-of-freedom trajectory, whose first part is executed w.r.t. reference frame A, and at the instant of a sensor-event (M_{2000}), the switching to reference frame B occurs. When implementing real-world robot manipulation tasks, this switching capability is essential for the sensor-based execution of Motion/Manipulation Primitives [7]: here, the execution of a single primitive ends at an arbitrary (unpredictable) state of motion, and the succeeding primitive has to start from this state, but this primitive may use another reference frame.

B. Unforeseen Switchings of Control State Spaces

Analogous to the new on-line frame switching capability, robot motion controllers become furthermore able to switch the control state space from one control cycle to another. As a very simple example of this new capability, Fig. 3 depicts a simple r-φ-manipulator for illustration purposes. The first part of the illustrated path is executed by a Cartesian motion controller, and at $t = 1830\,ms$, an unpredictable sensor event happens. Form the control cycle on, at which this event is detected, the motion is continued by the joint space controller, which receives its set-points from the *Reflexxes Motion Library* that instantaneously provides a joint space trajectory. As a result, jerk-limited trajectories can be generated in any moment of switching and continuous motions are guaranteed in any situation.

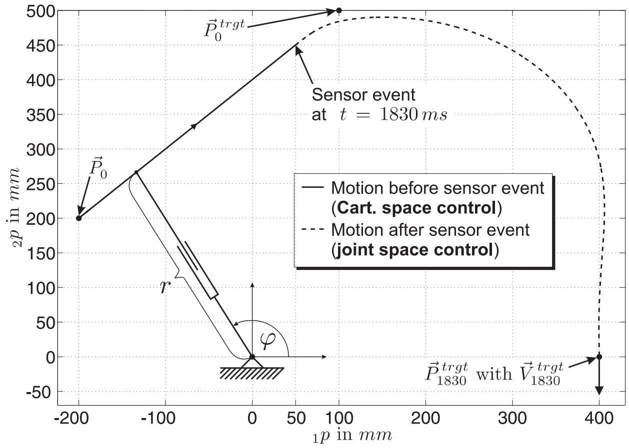

Fig. 3. An r-φ-manipulator, which executes a Cartesian motion command, that is unexpectedly interrupted at the position ${}^{Cart}\vec{p} = (50, 450)\,mm$ (solid line). Immediately after the interruption, the motion is controlled in joint space (dashed line) until the target state of motion has been reached.

C. Deterministic, Instantaneous Reactions to Sensor Signals

Using a *Reflexxes Motion Library* enables robots and systems to perform a kind of *robotic reflex*. As the motion generation library is integrated in the inner most control loops, robot reactions to *unforeseen* events can happen *instantaneously*. In the moment an event is triggered by a sensor signal, *safe, deterministic, and instantaneous* reaction strategies can be configured and executed, such that collisions can be prevented much easier and with shorter reaction times or a switching from sensor-guided to trajectory-following motion control (or vice versa) can be performed (cf. Fig. 4). As the OTG algorithm always calculates the (only) *minimum-time* solution, it is guaranteed that robot systems always behave deterministically: the same input values always lead to the same output values.

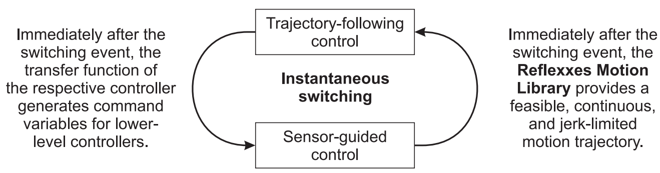

Fig. 4. The *Reflexxes Motion Libraries* enable instantaneous switchings between sensor-guided robot and trajectory-following motions (cf. [4], [5]).

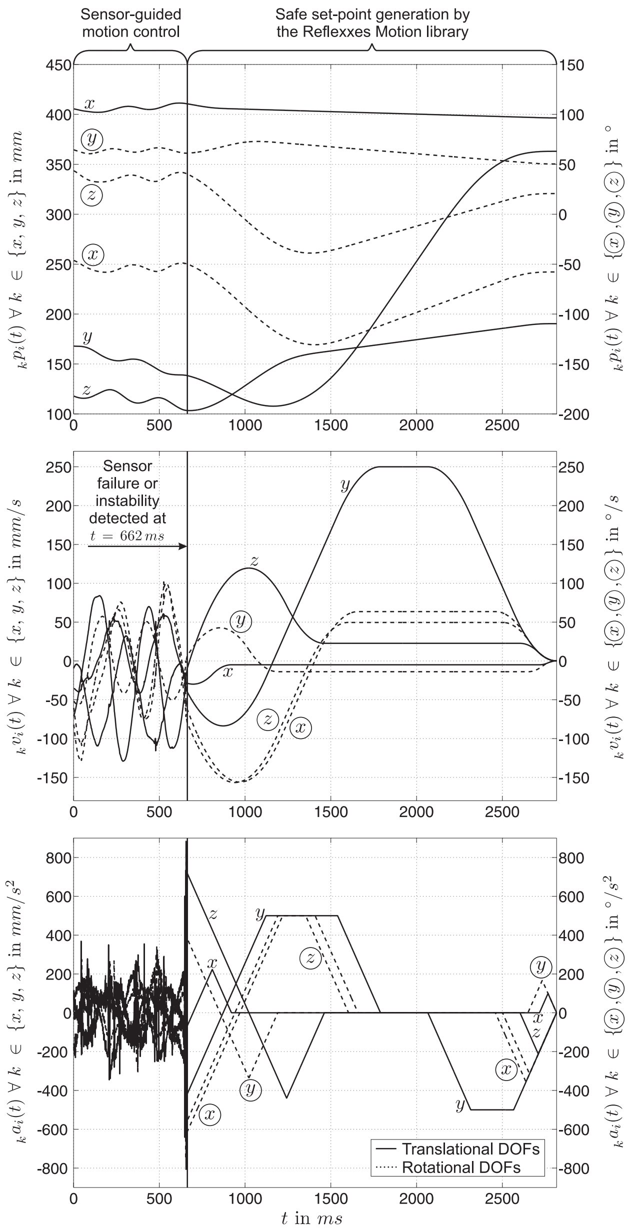

Fig. 5. Position, velocity, and acceleration progressions of a six-degree-of-freedom robot using a Cartesian motion controller. At $t = 662\,ms$, a sensor failure is detected, and the controller immediately switches from sensor-guided to trajectory following control in order to keep the system stable (cf. Fig. 6 and [8]).

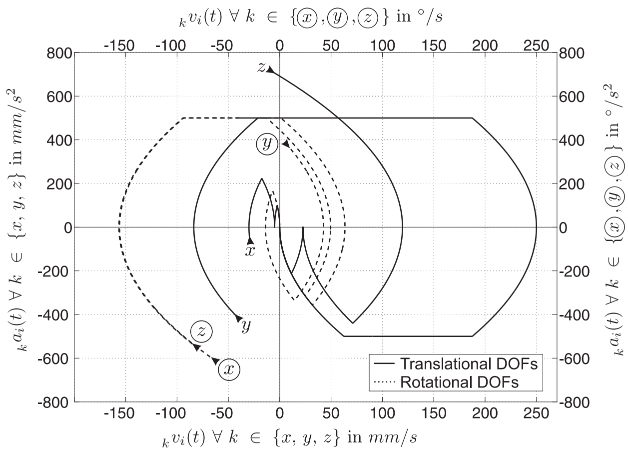

Fig. 6. Corresponding to Fig. 5, this diagram illustrates the six trajectories in their velocity-acceleration plane from the moment of switching on (i.e., in the interval $662\,ms \leq t \leq 2816\,ms$). All trajectories terminate in an equilibrium point of the underlying control loops, which is an essential feature to assure *overall stability*.

D. Safe and Stable Reactions to Sensor Failures

Safe and task-dependent reactions to sensor failures are very essential when sensors are integrated in robot motion controllers. Based on a *Reflexxes Motion Library*, a safe and continuous motion can be calculated in the same control cycle, at which the failure is detected (e.g., force/torque sensor malfunction or vision system malfunction). This way, safe jerk-limited motions can be guaranteed in any situation [8]. For a simple illustration, Fig. 5 shows a robot motion trajectory, which first is generated by a closed-loop controller (sensor-guided) and at the control cycle at $t = 662\,ms$, a sensor failure is detected and the *Reflexxes Motion Library* instantaneously provides set-points for lower-level controllers that lead to a safe, stable, and continuous robot motion.

E. Simple Visual Servo Control

The usage of computer vision systems in robotic applications leads to significant advantages and lets us realize new applications. Instead of using cameras only for the calculation of robot target positions, it will be even more advantageous if the signals of cameras and image processing systems are fed to low-level controllers (visual servo control). Problems can appear if the vision system does not work properly (e.g., because a human or an obstacle accidently covers one or more of the cameras). Using one of the Reflexxes Motion Libraries as an intermediate layer, that is, between the image processing system and the low-level controllers, leads to the important advantage that continuous motions can always be guaranteed (even if the vision system does not work in real-time or at low sample rates).

F. Stable Switched-System Control

The integration of multiple sensors of one or different kinds generally leads to more opportunities for for robot motion controllers. In order to use sensors for sensor-guided and sensor-guard robot tasks, their signals are used in the feedback loops of low-level controllers, such that a hybrid switched-system is established [8]. Keeping such systems stable is a difficult task. By using the *Reflexxes Motion Library* as one control submodule in the hybrid switched system, this module can always take over control (i.e., in any arbitrary state of motion) and generate set-points for lower-level controllers that guide the system to a safe equilibrium point. To illustrate this essential feature in a simple way, Fig. 6 exemplarily shows the motion of Fig. 5 in its velocity-acceleration plane from the moment of switching on.

III. The Library Interface

The application interface of the library is very simple: one single C++ class offering only one method has to be integrated in existing projects and systems. The constructor determines the control cycle time and the number of degrees of freedom; the main method of the class only requires three arguments: a data structure containing the input values, a data structure containing the output values (cf. Fig. 1), and an optional set of flags.
Four different Types of libraries are available:

Reflexxes Type I Motion Library This library is the most simple one. Only target positions can be specified, and the resulting trajectory is not jerk-limited.

Reflexxes Type II Motion Library Same as Type I, but target velocity vectors that are exactly reached at the desired target position can additionally be specified.

Reflexxes Type III Motion Library Same as Type I, but the resulting trajectories are jerk-limited, which leads to a significant reduction of wear and excitations of mechanical vibrations. Furthermore, a better trajectory following behavior is achieved.

Reflexxes Type IV Motion Library This is the most advanced library: a combination of the Type II and III library. The resulting trajectories are jerk-limited, and a target velocity vector that is exactly reached at the desired target position/pose can be specified; its interface is shown in Fig. 1.

IV. First Projects

To demonstrate the fundamentally new possibilities for the control of industrial, humanoid, and service robots, the *Reflexxes Motion Libraries* is being used in several robotics projects, all of which significantly benefit from the new technology. It is being used in the Stanford Whole-Body Control Framework [9] running on the PR2 platform of Willow Garage [10] and on the Meka arm [11], a first ROS [12] package using the Reflexxes Type I Motion Library is available, robot applications using the the KUKA Fast Research Interface [13] and the Stäubli [14] Low-Level Interface [15] were setup, and the Honda Company [16] uses it in control units of humanoid robots. Further projects are approaching and new suggestions are always very welcome.

V. Summary

The Reflexxes Company [3] is a spin-off company working on technology transfer projects in order to bring the latest framework of on-line trajectory generation widely into practice. The *Reflexxes Motion Libraries* feature very simple and clear interfaces, such that they can easily be integrated in existing control systems for industrial, humanoid, medical, mobile, and service robots. Feasible, smooth, and continuous robot motions can safely be provided in one low-level control cycle, such that *instantaneous* reactions to *unforeseen* events become possible. For instance, safe reactions to *sensor failures*, unforeseen reference frame and state space switchings, simple visual servo control, and the realization of stable switched systems using multiple sensor signals can easily be realized now. All these features are important for the execution of sensor-based robot motions, and they give the capability of performing reflex motions to robots.

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