Verifiably Safe Human Robot Assisted Dressing

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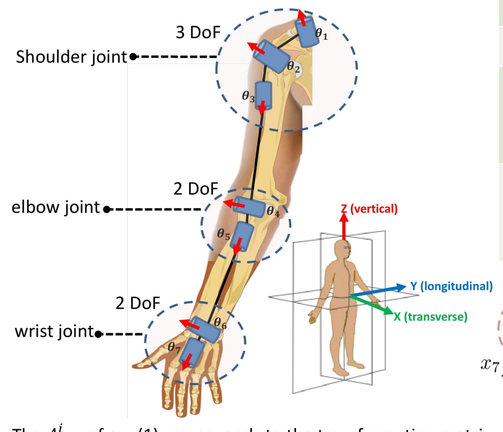
Introduction

To ensure the safety and intuitiveness of dressing assistance robot, two key problems need to be addressed. The human-robot interface must be intuitive to use and provide guarantee the robot's action will not cause any harm to people.

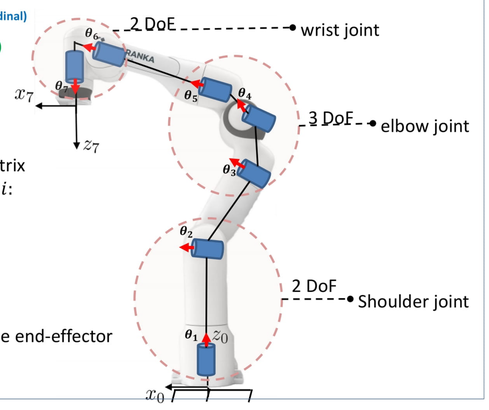
A key objective of our project is to ensure safety by using multi-modal inputs accounting for environment dynamics, human errors and ergonomic limits. Furthermore, to narrow the divide between the state-of-the-art research in Physical Human Robot Interaction (pHRI) and formal verification through the integration of safety guarantees, verification, and automated synthesis in the context of pHRI.

Kinematic Chain of a Human/Robot Arm

A kinematic chain is a set of rigid bodies, connected by joints.



DH Link and Joint Parameters	
a_{i-1}	Link length, mutual perpendicular distance between 2 axis
α_{i-1}	Link twist, angle from axis $i-1$ to i
d_i	Link offset, the offset distance of one link to the next (from the common axis)
θ_i	Joint angle, rotation of link with respect to its neighbour (along common axis)



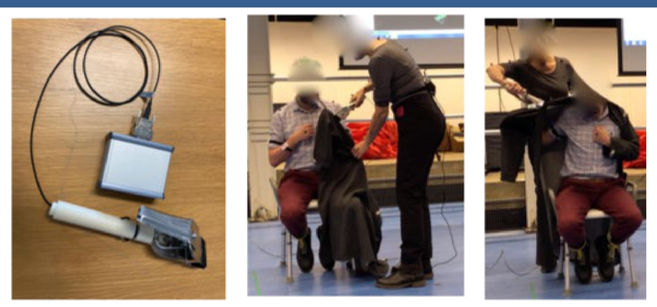
The A^i_{i-1} of eq. (1) corresponds to the transformation matrix between the two sequential coordinate frames $i-1$ and i:

$$A^i_{i-1} = \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i c\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The transformation matrix from the shoulder position, to the end-effector T^7_1 is given by eq. (2)

$$T^7_1 = \prod_{i=1}^{7} A^i_{i-1} \quad (2)$$

Human-Human Trial

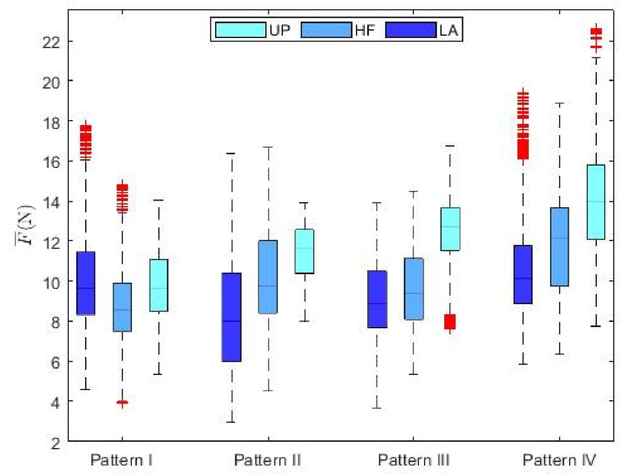


(a) (b) (c)

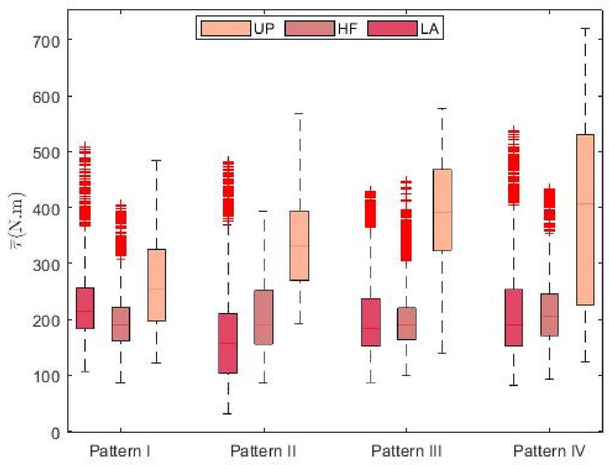
The occupation therapist (OT) assisting the volunteer with dressing using the dressing force acquisition handle (a), in b) the OT is pulling the garment over the left hand, and in c) the OT is holding the garment in position for the volunteer to put their healthy right arm into the sleeve.

Upper limb spasticity patterns				
Segment	Pattern I	Pattern II	Pattern III	Pattern IV
Shoulder	Int. Rot./Abd.	Int. Rot./Abd.	Int. Rot./Abd.	Int. Rot./Abd.
Elbow	Flexion	Flexion	Flexion	Flexion
Forearm	Supination	Supination	Neutral	Pronation

The box plots represent average forces and torques applied on the garment by the OT at different points on the volunteers' upper body segments S = {LA, HF, UP}, obtained from sample size N={4251, 1701, 770}, respectively. The results suggest that when the magnitude of the force is increased, the amount of torque used also increased.

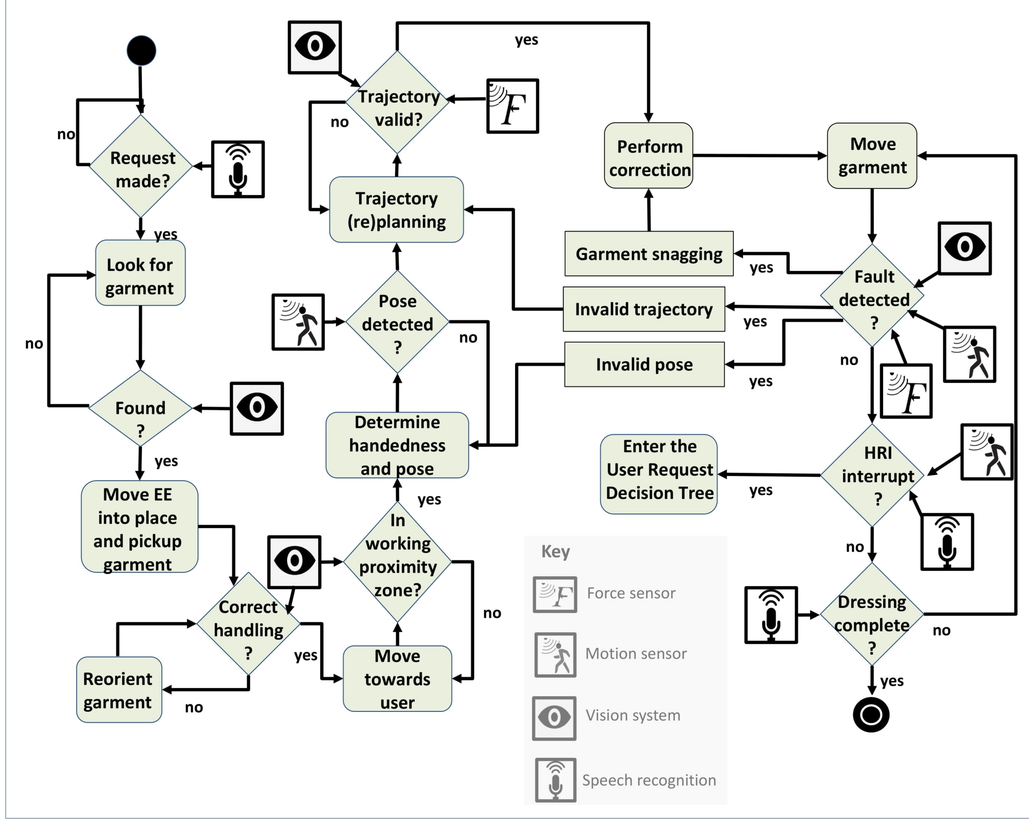


The average force applied, on the garment, in contact with the volunteers' upper body segments.



The average torque applied, on the garment, in contact with the volunteers' upper body segments.

Flow of The Autonomous Assisted Dressing

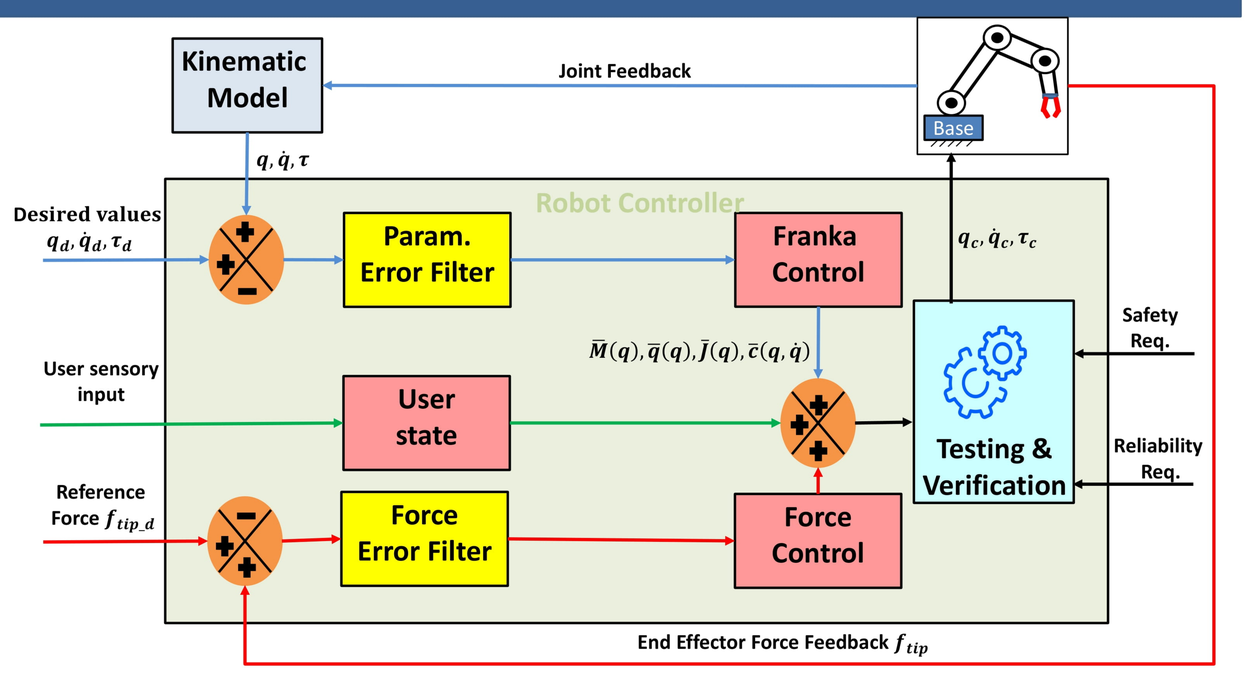


ID	System Requirements
SR1	The robotic system will autonomously execute dressing trajectories
SR2	The robotic system can use non-vision (haptic) based feedback to update its planning strategy
SR3	The robotic system communicates through speech and GUI with the user
SR4	The robotic system can detect environmental and user changes in real time and update its planning
SR5	The robotic system can detect environmental and user changes in real time and update its planning

ID	Functional Requirements
FR1	The robot maintains up to $f_{max}(N)$ forces between the person and the garment during dressing
FR2	The robotic system has user tracking ability (skeleton) to detect up to 5cm and 5 degrees accurate poses
FR3	The robotic system detects changes in the environment, for example level of lighting, noise, user related changes.
FR4	Robot algorithm enables learning to guarantee personalization and adaptation.

Testing and Verification of the Robot Controller

- **Search-based Testing**
  - Automated test generations.
  - Compute fitness of the testcase as optimization problem.
  - Using metaheuristic algorithms such as Genetic Algorithms
- **Stressing Properties**
  - For example, there is an upper limit on force applied – we can simply optimize (maximise) force.
- **Runtime Verification**
  - Verify safety properties of the autonomous controller from a discrete-time Markov chain, using probabilistic model checker PRSIM



Where, $q, \dot{q}, \tau \in \mathbb{R}^n$, are the position, velocity and torque vectors for each joint (n = 7), $[\cdot]_d$ are the desired values and $[\cdot]_c$ are the commanded values. The Franka control, computes the numerical values for inertia matrix $\bar{M}(q)$, the gravity vector $\bar{g}(q)$, the Jacobian matrix $\bar{J}(q)$ and the Coriolis term $\bar{c}(q, \dot{q})$. These data are sent to the Verification engine for trajectory planning.

Key Features

- Vision System to detect garment
- Movement and gripper control
- Sensors to detect user position
- Speech recognition system
- 7 DoF with torque sensors at each joint, allowing adjustable stiffness/Compliance
- Force/torque control
- Human-robot interaction

Safety Requirements

- An assistance-robot must be controlled in such a way that humans and robots are able to safely operate within shared space.
- The dressing assistant-robot's operation bandwidth (i.e., velocity) must be restricted to allow the user to fully understand and predict the motion of the robot.
- The collision of a dressing assistant-robot with a stationary person must not result in any serious injury to the person.

Safe Robot Control

- Force of the manipulator is a control which is used to guarantee safe interaction between a person and robot in the real world. Where, pre-collision safety is concerned with collision forces exerted at the time of impact while post-collision safety is concerned with forces exerted by a robot after the impact.
- The results from our Human-Human dressing trials will help further development of control algorithms for safe autonomous operations of robot-assisted dressing.