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HolisafeHRC: Holistic Safety Concepts in Human-Robot Collaboration

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Abstract— **The success of human-robot collaboration (HRC) systems is currently facing problems related to unsolved issues in terms of safety. Standards have been established that provide a framework for implementation of such systems, but the actual safety assessment is still very difficult due to the overall complexity of HRC systems. This creates barriers for potential users and system integrators, which is a limiting factor in terms of industrial exploitation. The HolisafeMRK project addresses the safety issues in HRC and aims to develop a method for risk assessment analysis. This paper presents an overview of HolisafeMRK, a methodology for risk assessment analysis, and intermediate results.**

I. INTRODUCTION

Collaborative Robots (cobots) unlike industrial robots, work in close proximity with human co-workers, sharing common work space. Safety is vital when it comes to fulfilling collaborative operations. The safety requirements for industrial robots are described in ISO 10218-1:2011 and ISO 10218-2:2011 [7][8], which also include standards for collaborative robots. The standards state that identification of hazards is necessary and adequate measures have to be taken, in order to eliminate or reduce the risk associated with collaborative operations.

In the literature there are many approaches dealing with safety aspects in human-robot collaboration. The work in [11] presents a collision model to evaluate the safety in human-robot collaboration, which is useful in finding design parameters. The design metric for the assessment of the severity of a transient physical contact between a robot and human body region is presented in [15]. The other safety approaches are based on safe designing of shared work places, where collaborative tasks are to be carried out [12][5]. The experimental results based on ISO/TS 15066 standards for safe human-robot collaboration are presented in [13]. Most of the research work is focusing either on designing of safe manipulators or finding the impact forces on dummy human subjects. In contrast to the existing approaches, the project HolisafeMRK deals with safety aspects at application level.

The main goals of the HolisafeMRK project are:

- A simulation software called CASA tool (Computer Aided Safety Assessment) is being developed, which simulates the models that represent the manufacturing process to determine safety-relevant critical areas and possible collisions. Thus allowing the robot integrators to make the risk analysis beforehand, giving an opportunity to take proper actions before deployment of the applications in a real world scenario.
- As robots and operators work in close vicinity, tactile sensors are key elements in HRC systems [4]. Therefore, application specific tactile sensors are developed along with illuminated interfaces.
- Conventionally, human co-workers interact with the robot either with the help of teach pendants or Graphical User Interfaces (GUIs). The HolisafeMRK project introduces new interaction modalities by integrating tactile sensors directly on the robot that allow for a more fluent interaction with the robot.
- Furthermore, the developed technologies are tested on a pneumatic robot.

The contributions of this paper are as follows:

- First, a methodology for an assessment of the safety in a human robot collaboration process is presented.
- Then, the implementation concept of the described methodology against an industrial use case is provided.
- Finally, the initial results of the risk assessment by calculating the collision forces and developed capacitive sensors are presented.

The remaining part of the paper is organized as follows: In Section II, the methodology of the proposed approach is described together with the contact forces and the transferred energy relations, and the tactile sensors. The industrial use case is given in Section III. Section IV describes the implementation details and the initial results. Finally, some concluding remarks and the planned future work are given in Section V.

II. METHODOLOGY

Figure 1 depicts the work flow of the CASA tool. The simulations are performed with pre-defined trajectories. Every use-case defines trajectories that are specific to the application. Initially the robot model as well as the robot trajectories are loaded into the simulation. Then the critical points are identified during the simulation with respect to the robot pose. The associated risks are assessed by comparing the computed forces with safety limits proposed in the standards. If the collision forces are within the safety limits, then use case is safe to test it real scenario. Otherwise, various simulations are carried out to alter the robot trajectories and safety values to bring the collision forces to the safe limit. Thus safety of the human co-worker is ensured by foreseeing the potential risks and taking corresponding measures before actual integration takes place.

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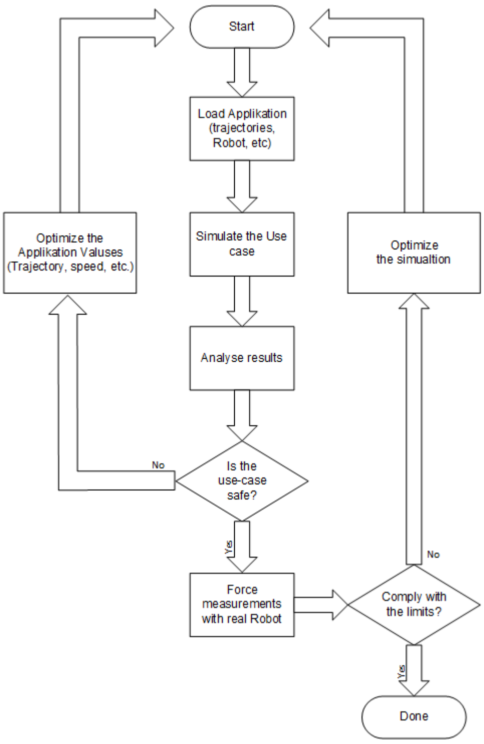

Fig. 1. CASA Tool: work flow

A. Collision Forces and Transferred Energy

A six-DOF robot arm is considered for the simulation as it is widely used. Let l_1 to l_6 be the link lengths of the manipulator; m_1 to m_6 be the masses; I_1 to I_6 be the moments of inertia; l_{c1} to l_{c6} be the distances from the each link to its center of mass; r_1 to r_6 be the radius of the cylindrical links; q_1 to q_6 be the joints angles; $\dot{q}_1$ to $\dot{q}_6$ be the velocities at the corresponding joints; u is the direction vector in which the robot end-effector is moving. Given these parameters, now the effective mass m_R of the robot is given in the Equation 1 [10].

$$m^{-1}{}_R = u^T[(J(q)M^{-1}(q)J^T(q))]u \tag{1}$$

Where $J(q)$ and $M(q)$ are the Jacobian matrix and inertia matrix of the manipulator, q is the joint angle vector, and u is the direction vector. The relation between transferred energy (E) and the collision force F is given in the following Equation 2 [9].

$$E = \frac{F^2}{2K} = \frac{1}{2}\mu v_{rel}^2 \tag{2}$$

Where K is the effective spring constant of the specific human body region. v_{rel} is the relative speed between robot and human body region. μ is the reduced mass between two-body system, which is given in the Equation 3.

$$\mu = \left(\frac{1}{m_H} + \frac{1}{m_R}\right)^{-1} \tag{3}$$

Where m_H is the effective mass of the human body region and m_R is the effective mass of the robot. The relative speed

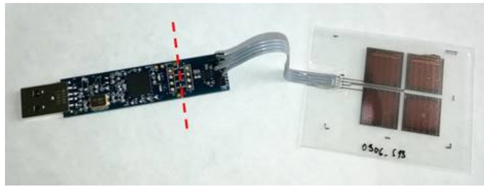

Fig. 2. Capacitive flexible sensors with four electrodes printed on PET connected to the evaluation board with TI FDC1004 capacitive interface circuit

(v_{rel}) between robot and human body region is given in Equation 4.

$$v_{rel} = \frac{F}{\sqrt{\mu k}} = \frac{pA}{\sqrt{\mu k}} \tag{4}$$

where p is the maximum allowed pressure value [9]. Effective masses and spring constants of different human body regions are given in Table I.

TABLE I
EFFECTIVE MASSES AND SPRING CONSTANTS OF HUMAN BODY REGIONS [6] [14]

Body region	Effective spring constant (k)(N/mm)	Effective Mass (M_H) (kg)
skull and forehead	150	4.4
Face	75	4.4
Neck	50	1.2
Back and shoulders	35	40
chest	25	40
Abdomen	10	40
Pelvis	25	40
Upper arm and elbow joints	30	3
Lower arm and wrist joints	40	2
Hands and fingers	75	0.6
Thighs and Knees	50	75
Lower legs	60	75

B. Capacitive Sensors

The capacitive sensors enable new methods of interaction with robots. For example, restarting an existing application without need of using a teach pendant. The work was focused on the design of a capacitive structure for proximity and touch detection, which can be applied to a robot for preliminary testing. PET (Polyethylene terephthalate) substrate was chosen due to its flexibility and as a relatively easy processable material. Jetting optimization for two different silver inks has been done with a resolution of printed lines down to 200 µm. In parallel, printing tests of conductive and insulation inks on different kinds of *AIRSKIN*® [1] have been performed. The capacitive sensor is shown in Figure 2.

III. USE-CASE DEFINITION

The industrial use case of palletizing application called Flexpalletizer from Haba Packaging GmbH is shown in Figure 3.

The set up consists of a robot (UR10), a conveyor belt to carry pancake boxes, and the pallets on which the pancake

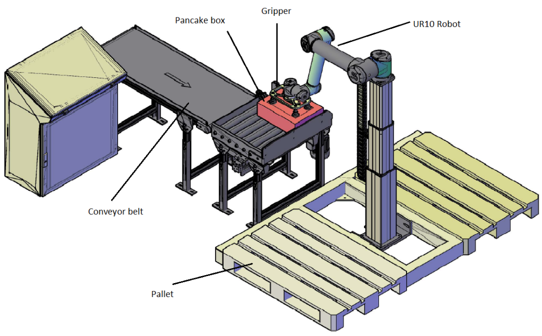

Fig. 3. Flexpalletizer Use Case: conception of robot picking pancake box from conveyor belt [3]

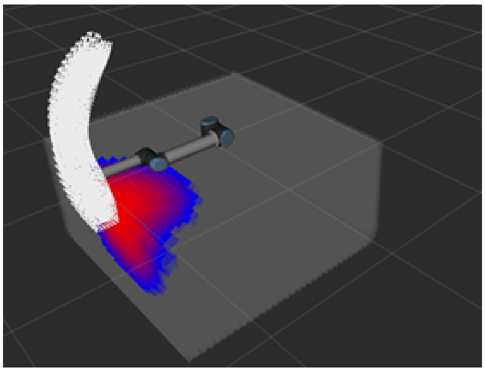

Fig. 4. Robot Visualization in Rviz with critical points (red color) along defined trajectory (white color)

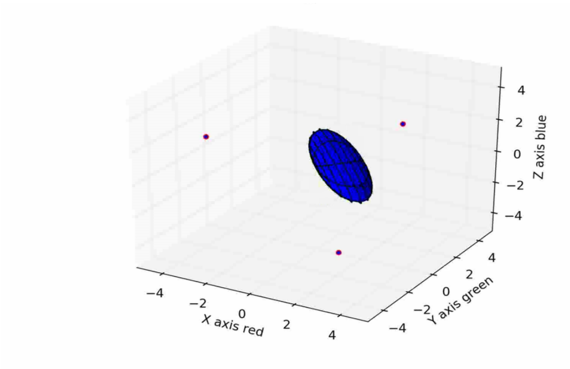

Fig. 5. Robot end-effector velocity ellipsoid

boxes to be stacked. The goal of the use case is a collaborative process, where the robot picks the pancake boxes from the conveyer belt and places them on the pallets. The worker then labels them accordingly. Given the process that requires human and the robot work in close proximity, safety of the human worker is crucial. In order to perform the risk assessment, the complete process is divided into following sub tasks; 1. Robot moving from its home position to pick position 2. Picking the box with gripper manipulation. 3. Moving from pick position to place position. 4. Manipulating the gripper to place the object. 5. Moving back to home position or back to pick position. 6. Worker labeling the stickers on the box. Tasks 2 and 4 are not relevant concerning safety, as robot stays stationary. The remaining robot movement tasks could have a potential collision possibility with human co-worker sharing the workspace.

The task that is performed by human co-worker, for example, if the the human worker is trying to take an object from the pallet and the robot approaches the pallet at the same time, could lead to a potential collision scenario. Some examples of such collision scenarios could include:

- Scenario1: Robot approaching from above; could result in a head-on collision
- Scenario 2: Robot approaching from sideways; could result in collision with the arm.
- Scenario 3: Robot placing a box while worker is labeling the boxes; could press the hand against other boxes

IV. Implementation and Initial Results

A. CASA Tool

A simulation environment of ROS is used together with Kinematics and Dynamics Library(KDL). An URDF (Unified Robot Description Format) model is used to define the geometric relations between robot links and dynamics.

The visualization of the robot in Rviz is depicted in Figure 4. It shows the simplified scenario with a robot moving along the trajectory (white overlay). As the end-effector approaches to close vicinity of the work table, it is identified as potential collision area (red color). The force computations for quasi-static contact are considered only for the potential collision areas. The velocity ellipsoid of an end-effector at an arbitrary pose is seen in Figure 5. The robot moves fast along the long axis of the ellipsoid compared to the short axis of the ellipsoid. Therefore, possible collision forces are greater along the large axes.

The results obtained from the simulation will get compared to the results of the dynamic force measurement device (KMG 500 KOLROBOT) for the validation. It has a spring constant of 75 N/mm, which is equal to human hand region according to the ISO/TS 15066 [9]. The comparison of the estimated forces from the robot with dynamic force measurement is given in Figure 6. The duration of the collision is 180 ms. The collision force in impact direction i.e. z direction stayed approximately at 100 N from 25 ms to 135 ms, which is with in the safety limits. After this, the robot reacted to the collision and retracted from the collision point and the collision force becomes zero.

Figure 7 shows the collision test results of UR10 robot with configured parameters such as different velocities and the force value of 150 N at tool center point. The collision tests with a speed of 50 mm/sec and 100 mm/sec have impact forces within the safety limits as specified in the standards. At other speeds, safety limits are violated indicating that a maximum velocity of 100 mm/sec is allowed for that robot end-effector pose in order to meet safety criteria.

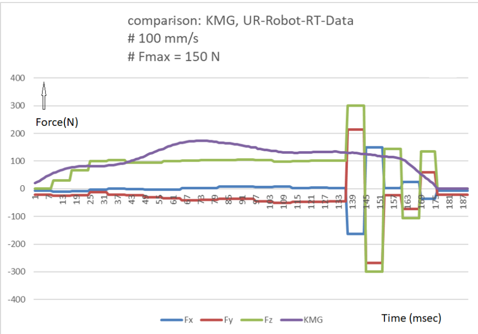

Fig. 6. Force Measurements: Dynamic force measurement device vs estimated forces from robot simulation

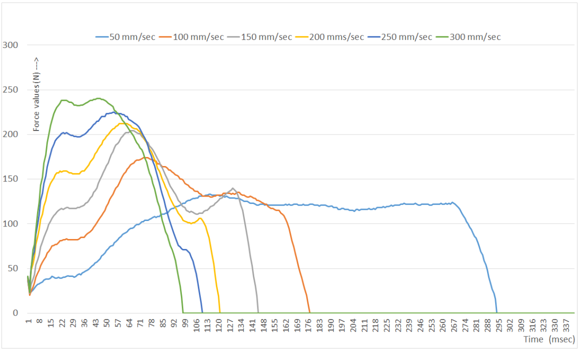

Fig. 7. Collision force measurements

B. Capacitive Sensors

Capacitive elements were printed on PET substrates using LP50 printer and industrial printing head Dimatix Spectra-128. Conductive layers were laminated with a thin PET foil, which serves as a protection layer and also as a dielectric layer for touch sensing. The capacitive structure is divided into four sections of each 15 mm x 15 mm in size, the capacitance of each section can be evaluated separately. The FDC1004 [2] was used for sensor evaluation. It is a high-resolution, 4-channel capacitance-to-digital converter for implementing capacitive sensing solutions. Each channel has a full-scale range of ±15 pF. The FDC1004 also includes shield drivers for sensor shields, which can reduce EMI interference and help focus the sensing direction of a capacitive sensor. The electrode size allows detection of the human hand from a distance of 10 cm and reliable touch detection as is depicted in Figure 8.

V. CONCLUSIONS AND FUTURE WORK

This paper presents a concept for assessment of the safety for human-robot collaborative process. The presented results are verified with real time collision tests, which are promising.

As part of the future work, the foreseeable tasks are; First, the complete scenario of the palletizing use case will be taken into the scene for identification of critical areas and computation of possible collision forces. The simulations are extended for different human body regions by taking into account of different spring constants. The tactile sensors will be printed and tested on different materials in order to study the capacitance characteristics. Then capacitive sensors will be integrated on the robot which enable a set of functionality, for example switching of the applications, which in turn lays the pavement for the new methods of interaction. Finally, the entire application will be tested in a real scenario.

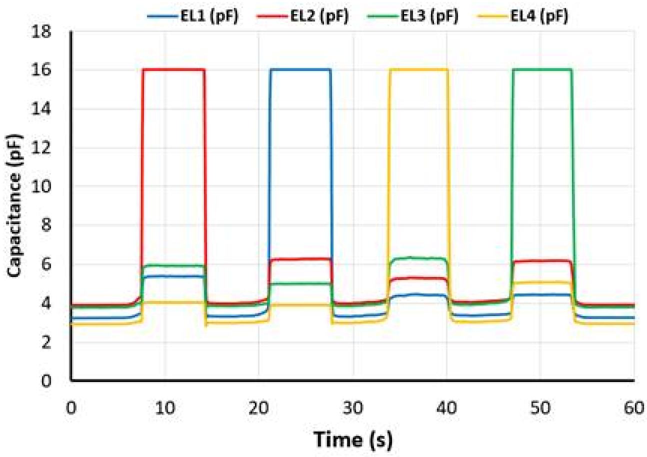

Fig. 8. Record of measurement of touch detection on segments (EL1, EL2, EL3, EL4) of the printed capacitive sensor.

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