Report on safety and requirement for:

Human-Robot Collaboration in object manipulation

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Contents

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Forward

Cooperation with humans is an important challenge for robotics, as robots will come to work side by side with people. CORSMAL is a European project that considers typical cooperative scenarios in which, a human and a robot hand over previously unseen objects and whose physical proprieties such as dimensions, shape, weight.. are unknown to the robot, such as, a glass or a cup that is partially filled with an unknown filling (e.g. a liquid), which makes it extremely hard to determine affordance for automatic algorithms (e.g. computer vision) and the appropriate grip points: characterising partially observable objects is indeed among the most critical issues to instantiate appropriate robot actions.

In these new working conditions, rules must be established in order to ensure safety of both the human and the robot when performing a task. This report 'Human-Robot collaboration in object manipulation' is a guideline for safety requirement in cooperative scenarios based on ISO Standards (ISO/TR 20218-1/2:2017,ISO/TS 15066:2016) made for the CORSMAL Project. It presents the risks that might rise when performing the collaborative task considered in the project and how they can be reduced.

Normative references

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The following ISO Standards are referred to in the text in such a way that some or all of their content constitutes requirements of this document.

ISO 10218-1:2017, *Robotics — Safety design for industrial robot systems — Part 1: End-effectors.*

ISO 10218-2:2017, *Robotics — Safety design for industrial robot systems — Part 2: Manual load/unload stations.*

ISO 15066:2016, *Robots and robotic devices — Collaborative robots*

Terms and definitions

- **compliant**
  exhibiting deformation of material or mechanism when subjected to a force.
  EXAMPLE Compliant linkage, compliant surface. (SOURCE ISO/TR 20218-1:2018)

- **mechanical interface**
  end-effector flange mounting surface at the end of the manipulator to which the end-effector is attached.(SOURCE ISO/TR 20218-1:2018)

- **end-effector**
  device specifically designed for attachment to the mechanical interface to enable the robot to perform its task.
  EXAMPLE Gripper, welding gun, spray gun.(SOURCE ISO/TR 20218-1:2018)

- **gripper**
  end-effector designed for grasping workpieces.(SOURCE ISO/TR 20218-1:2017)

- **fixture**
  device used to fixate an item as part of the handling or assembling process in a robot system, but not as an end-effector. (SOURCE ISO/TR 20218-1:2017)

- **robot application**
  system comprising an industrial robot system (industrial robot, end-effector, workpieces and any machinery, equipment, devices, external auxiliary axes or sensors supporting the robot in performing its task) and any obstacle or object within the robot system workspace that has influence on the risk assessment of the workspace. (SOURCE ISO/TR 20218-1:2017)

- **impeding device**
  any physical obstacle (low barrier, rail, fixture, etc.) which, without totally preventing access to a hazard zone, reduces the probability of access to this zone by offering an obstruction to free access. (SOURCE ISO/TR 20218-2:2017)

- **manual load/unload station**
  part of the robot system designed for the direct manual intervention for the placement and removal of parts or workpieces for processing by the robot system. (SOURCE ISO/TR 20218-2:2017)

- **operator**
  person or persons given the task of installing, using, adjusting, maintaining, cleaning, repairing or transporting machinery. (SOURCE ISO/TR 20218-2:2017)

- **collaborative operation**
  state in which a purposely designed robot system and an operator work within a collaborative workspace. (SOURCE ISO/TS 15066:2016)

- **power**
  mechanical power mechanical rate of doing work, or the amount of energy consumed per unit time. (SOURCE ISO/TS 15066:2016)

- **collaborative workspace**
  space within the operating space where the robot system (including the workpieces) and a human can perform tasks concurrently during production operation. (SOURCE ISO/TS 15066:2016)

- **quasi-static contact**
  contact between an operator and part of a robot system, where the operator body part can be clamped between a moving part of a robot system and another fixed or moving part of the robot cell. (SOURCE ISO/TS 15066:2016)

- **transient contact**
  contact between an operator and part of a robot system, where the operator body part is not clamped and can recoil or retract from the moving part of the robot system. (SOURCE ISO/TS 15066:2016)

- **protective separation distance**
  shortest permissible distance between any moving hazardous part of the robot system and any human in the collaborative workspace. (SOURCE ISO/TS 15066:2016)

- **body model**
  representation of the human body consisting of individual body segments characterized by bio-mechanical properties. (SOURCE ISO/TS 15066:2016)

- **Subject**
  person or persons interacting with the robot to perform a task (e.g. handover)

Introduction

During the last decades robots have become an irreplaceable part of the industry, as they can perform better than humans when it comes to carrying heavy loads, executing tasks with high speed and precision, or operating in unreachable/hostile environments.

Collaborative robots are one of the fastest growing segments of robotics, they are designed to augment humans capabilities and not to replace them. In collaborative manipulation, humans and robots interact together in order to perform tasks. Handing over objects and receiving them is a basic and essential capability that robots must possess. Although, this capability may appear simple as humans perform handovers flawlessly, it is very difficult to replicate in robots.

Today's robots have shown successful skills on grasping static object for which physical proprieties are completely known, but robots perform object handover in a limited manner: typically, the robot holds an object statically in place and waits for the human to take it. This is far from the fluid handover between humans.

The CORSMAL project proposes to develop and validate a new framework for collaborative recognition and dynamic manipulation of objects with unknown fillings via cooperation with humans.

Human-Robot Collaboration

The robot-human collaboration can take many forms depending on how the human and the robot interact and share the workspace in order to perform a certain task, thus 4 majors types of collaborative robots (CobBot) can be identified:

- **Co-existential CoBots**, wherein a robot and a human work alongside another in the same workspace, but with no direct overlap in the minutiae of their labor.

- **Sequentially collaborative CoBots** directly work alongside humans, however, they don't work on the same product at the same time. These CoBots generally come before or after the human worker in the sequence of production.

- **Responsively collaborative cobots** are robots that respond directly to the actions undertaken by a human worker. They only operate insofar as they have a human executing more complicated tasks farther up the pipeline.

- **co-operational cobots** operate alongside humans at the same time while working together towards the same task.

These types are not exclusive, for example, a CoBot is part of two tasks, in the first one it works alongside with the human but does not work on the same piece, in the second task they work on the same piece at the same time, so this CoBot can be considered both Co-existential and co-operational.

In the CORSMAL project, the human and the robot will work together in order to perform successful handovers of object, they will share the same work space and will be interacting with the object at the same time, thus we will interest in the last type of robots which is Co-operational Cobots.

Approach

CORSMAL will develop a multi-modal and interpretable learning architecture Benchmark to improve the prediction accuracy of physical properties of unknown objects and partially observable objects (i.e. known objects filled with unknown filling), and to enable robust robotic manipulation. Manipulation here is concerned with determining the grasp to take the object from the human hand and to adapt the grasp forces to support the object's load once the object has been released by the human. The main challenge is to learn from scarce observations and to enable quick adaptation of the models to new situation (e.g. objects filled with new type of filling).

The CORSMAL project aims also to react swiftly to deviations from the expected behaviour and to perturbations of different nature like sensing and grip uncertainties, object occlusions or grip slippage. These challenges will be addressed by exploring partially-constrained learning architectures, and statistical machine learning for closed-loop control based on the fusion of vision, sound, tactile, force.

To focus the efforts and effectively measure progress, CORSMAL considers two use cases for a household manipulator.

Workcase scenarios

First use case scenario

In the first use case scenario CORSMAL will consider the handover of a previously unseen cup/glass and whose physical properties are unknown and should be inferred through multi-modal learning with unknown content: a human picks up a transparent glass or a plain cup and hands it over to the robot. The cup/glass can be either empty, half full or full of an unknown filling (e.g.water). The robot must infer whether the cup/glass contains liquid or not from observing the way the human picks up and carries the object i.e. the affordance[1] of the object.

[1] affordance is defined as the possibility of an action on an object or environment. (SOURCE JJ Gibson " The affordance theory")

The robot uses vision to infer the filling by exploiting the semi-transparency of the object and, based on its inference of filling, it decides on appropriate parameters for grasping the object (grasping points, stiffness). If the object slips from its fingers, the robot adapts its grip using algorithm and then updates the database with the new model's parameters Figure(1).

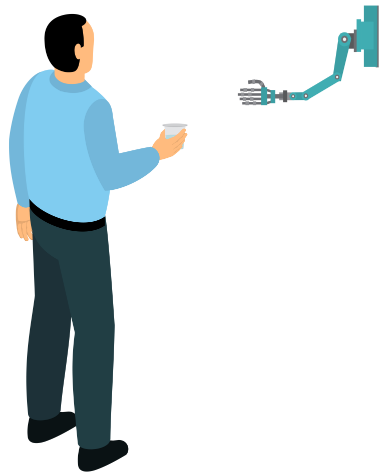

Figure 1: First case

Second use case scenario

In the first use case scenario CORSMAL will consider the handover of a previously unseen food box for which the physical properties are unknown(e.g. size, weight), also the box can be filled by unknown fillings(e.g. pasta or rice): the human picks up a food box and hands it over to the robot. As the human carries it, the content moves and makes noise, which the robot uses to complement vision in order to infer the content Figure(2).

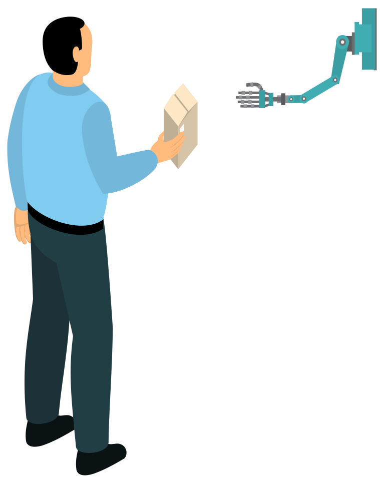

Figure 2: Second case

Both fragile transparent objects and non-fragile transparent objects will be used in the first use-case, as well as rigid boxes versus boxes made of very flexible material in the second use-case. Controllers will be adapted to the impedance at the fingers to handle fragility and to avoid inducing deformation on the flexible objects.

During the course of the CORSMAL projet partners will perform the evaluation of the developed algorithms on real robotic platforms, experiment will be held using robotic arms (universal robot, franka emika), equipped with end-effectors (robotiQ gripper , allegro hand), the specification for these equipment depend on the partners. Although partners may not share the same equipment , but they will all be using the same handover protocol, in which, the subject performing the handover stands facing the robot, the robot and the subject are separated by a table, and finaly the handover location is at the center of the table.

Risk Management

General

In the CORSMAL project the robot and the human will share the same workspace in which they will perform the hand over, before going into details in risk assessment we will first state 3 major condition that the system should respect in order to guarantee the safety of the human the robot and the object.

First, for both human and robot safety, all objects handed over to the robot should be light and with safe content. Safe for both human and the robot, for example if the cup to be handed over contains liquid and the handover fail the liquid may spill and damage the robotic hand. If the object to be handed over is heavy, it might be harm the human or damage the robot if it falls.

Second, since the human and the robot share the working space Safety concerns arising in the envisioned scenarios relate to unwanted contact between the human and the robot. Control of the robot must ensure that the robot does not enter in contact with the human in any other circumstances than through the object during the handover. The robot controllers will use monitoring of human motion (provided through vision) and stay away from the human workspace, by constraining the robot's workspace. This can be done at run time by treating the human as a moving obstacle or by constraining the robot's feasible space of motion, the robot controller will also be inherently compliant, ensuring safety in case contact may be unavoidable.

Finally, the safety of the object to be handed over must be ensured.

Safety requirement

ISO 10218-2:2011 describes safety requirements for the integration of industrial robots and robot systems, including collaborative robot systems. The operational characteristics of collaborative robot systems are significantly different from those of traditional robot system installations and other machines and equipment. In collaborative robot operations, operators can work in close proximity to the robot system while power to the robot's actuators is available, and physical contact between an operator and the robot system can occur within a collaborative workspace.

Any collaborative robot system design requires protective measures to ensure the operator's safety at all times during collaborative robot operation. A risk assessment is necessary to identify the hazards and estimate the risks associated with a collaborative robot system application so that proper risk reduction measures can be selected.

Collaborative system design

ISO/TS 15066:2016 sets the requirements for the collaborative system design, based on these requirements our system must take in consideration the following factors:

1. collaborative workspace, access and clearance:
    - delineation of the restricted space and collaborative workspaces.
    - the need for clearances around obstacles such as fixtures, equipment and building supports.
    - accessibility for operators.
    - the intended and reasonably foreseeable contact(s) between portions of the robot system and an operator.
    - access routes (e.g. paths taken by operators)
    - hazards associated with slips, trips and falls (e.g. cable trays, cables, uneven surfaces, carts)
2. ergonomics and human interface with equipment
    - clarity of controls.
    - possible stress, fatigue, or lack of concentration arising from the collaborative operation.
3. use limits
    - potential intended and unintended contact situations
4. transitions (time limits)
    - starting and ending of collaborative operation

Hazard identification

For hazard identification process the CORSMAL project shall consider the following:

1. robot related hazards, including:

   - robot characteristics (e.g. load, speed, force, momentum, torque, power, geometry, surface shape and material).

   - quasi-static contact conditions in the robot.

   - operator location with respect to proximity of the robot (e.g. working under the robot) ;

2. hazards related to the robot system, including:

   - end-effector and workpiece hazards, including lack of ergonomic design, sharp edges.
   - free cables related to the robot hazards(e.g. end effector cables), if the cables are nor not tightened and placed droparl, they may twist and damage the robot or the surrounding equipement.
   - operator motion and location with respect to positioning of parts, orientation of structures (e.g. fixtures, building supports, walls) and location of hazards on fixtures.

   - fixture design, clamp placement and operation, other related hazards.

   - a determination as to whether contact would be transient or quasi-static, and the parts of the operator's body that could be affected.

   - the influence and effects of the surroundings (e.g. where a protective cover has been removed from an adjacent machine, proximity of a laser cutter).

3. application related hazards, including:

   - process-specific hazards (e.g. temperature, ejected parts, welding splatters).

- limitations caused by the required use of personal protective equipment.

4. software related hazards, including:

   - Inaccurate 3D localization of the object to be handed over by the robot (The container), leads to errors in the control process, which may cause the object's filling to spill (e.g. water) and damage the robot of other electrical components.

   - Inaccurate 3D dimension estimation, leads to errors in the grasp planing process, if the estimated dimension is bigger than the real dimension, the object will slip and fall from the end-effector during the grasping, if the estimated dimension are smaller than the real dimension than the end-effector will crush the object in the grasping process, in both cases the object might be damaged and the fillings might damage the robot or the electrical components.

   - Inaccurate 3D localization of the human/subject grasp of the object, may lead to errors in the grasp control process of the robot, this could cause the end-effector to close and trap or hurt the subject's hand or fingers.

   - wrong/Inaccurate/unexpected robot path planning may cause the robot, the end effector to crush into the its surroundings (e.g. table, walls, screens, computer, or the human/subject), which might harm the human/subject and damage the robot, the end effector and it's surroundings.

Task identification

The CORSMAL project consider the following task:

1. the frequency and duration of subject presence in the collaborative workspace with the moving robot system.

2. human maneuvering, time between when the subject gets in contact with the cup and when the robot gets in contact with the cup.

3. dynamic handover, time between when both subject and robot are in contact with the cup.

4. robot maneuvering, time between when the subject is last in contact with the cup and when the robot is last in contact with the cup after delivery.

5. transitioning between the three phases of the handover (human maneuvering, dynamic maneuvering, robot maneuvering) .

6. the frequency and duration of contact between a subject and the robot with the object to be handed over.

7. automatic or manual restart of robot system motion after the handover process has been completed.

8. any additional tasks within the collaborative workspace.

Hazard elimination and Risk reduction

In the previous section hazard Identification, we analysed our system and determined the hazards related to our handover process, in addition to the outcome of the occurrence of these hazards on the Subject, the robot, and the object to be handed over. in this section we will proceed to the elimination of these hazards and the reduction of the risks related to them based on the ISO/TS 15066:2016 requirements for safe collaborative system design .

To ensure the safety of our system we will be setting the following measures:

1. **Stopping functions** During the handover process the subject shall have the means to either stop the robot motion at any time by a single action or have or have an unobstructed means of exiting the shared workspace.(e.g an emergency stop device, stopping the robot by hand).

2. **Supervisions of an operator** An operator should be present to monitor the conduct of the handover process, in case unpredictable errors relater to vision or path planning, the operator should be able to stop the robot.

3. **Separation distance** The robotic arm shall never get closer to the Subject than the protective separation distance, this distance must be calculated taking in consideration the speed of the robotic arm and the uncertainties

Body region	Maximum permissible force N
Skull and forehead	130
Face	65
Back and shoulders	210
Chest	140
Abdomen	110
Upper arms and elbow joints	150
Lower arm and wrist joints	160
Hands and finger	140

Table 1: Biomedical limits for permissible applied forces to body parts

related to the subject's and the robot's movements. The separation distance guarantees that the robotic arm never gets in contact with any part of the subject's body.(Refer to ISO 13855 for information on how to calculate the protective separation distance).

4. **Power and force limiting** Physical contact between the subject/human can occur either intentionally or unintentionally.The lack of information on the subject grasp provided by the visual system, may lead to unintentional contact between the end-effector and the subject's finger when the robot is reaching out to grasp the object, also unpredictable errors related to the control system, may lead to unpredictable robot movement that might harm the subject. to ensure the safety of the human when the contact occurs , we will set force limits based on the norms defined in ISO-TS:15066. Since the robot is installed on a high platform, the robot can only come in contact with the upper part of the subject's body. Table (1) shows the maximum permissible forces that can be applied to different parts of the subjects upper body (Source ISO-TS:15066) , these permissible forces must be set as the threshold that the robot can not surpass at any given time of the handover process.

5. **Speed limits** To reduce the risks related to unpredictable movements and unintentional contact, we shall set speed limits for the robotic arm and the end effector, these speed limits allows the subject or the operator to have enough time to react in case of unpredictable scenarios.

The hazard elimination and risk redaction sections set the list of the measures to be respected collaborative system design we consider in the CORSMAL project, as the partners in the project possess different robotic platforms, each partner must adapt it's platform and software design , so that measures are respected to fulfil the Safety requirement.