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CROWDBOT

Safe Robot Navigation in Dense Crowds

http://www.crowdbot.org

Technical Report

D 4.1: Physical Interactions between Robots & Humans

Work Package 4 (WP 4)
Simulation Tools for Robot Navigation in Crowds

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Executive Summary

The CROWDBOT project aims for tight navigation of mobile robots in a dense crowd and thus physical interaction (both contact and non-contact) between a robot and human crowd is anticipated. This report addresses our approach for modeling, analysis and experimentation of robot-human physical interaction. Here the term "physical" means that a robot will come close (i.e. non-contact) or in contact with a human or humans while it navigates and moves amongst them. Hence, physical interaction is all about physics, mechanics, locomotion and possibly bodily harm. The other related term "social interaction" refers to interpersonal, cultural and give-and-take exchange between two entities to avoid collision. This topic is outside the scope of this report. Here, we dedicate solely to the topic of robot-human physical interaction, also commonly annotated in the literature as pHRI (physical Human-Robot Interaction).

The report is divided into three main sections: 1) modeling of physical interactions, 2) bibliographic study of physical interactions and 3) case studies of physical interactions for robots that apply specifically to CROWDBOT.

Before we conduct live experiments with humans and a robot in a dense crowd environment, we will simulate their interactions using computer model based simulation tools to anticipate outstanding scenarios worth investigating further via real tests. Section 3 provides our computer simulation framework and planned efforts in this area. Note that a computer based physical interaction simulation tool does not exist for academic use or for commercial purpose. Therefore, we plan to modify existing robotic simulation tools to achieve our main goal.

Section 4 gives an extensive overview of physical interaction studies and a bibliographical reference to the original sources. Three focus areas are 1) Regulations and Standards, 2) Robot Manipulation and 3) Studies from the automotive industry. There exists a number of industry-wide and governmental regulations, standards and policies for safe operation of robots. However, they have yet to cover robotic navigation scenarios planned for CROWDBOT. The team plans to actively engage with regulation ad standards bodies and authorities and share our findings.

Two robots selected for CROWDBOT are the Pepper humanoid and the smart wheelchair. Since Pepper is a successful commercial product with wide use around the world for a number of years now, we provide an analysis of human-Pepper interactions in Section 5. This is followed by a summary of prior studies in physical interaction between humans and a human-operated motorized wheelchair. Both case studies serve as baseline before CROWDBOT introduces advanced navigation features via augmented sensors, artificial intelligence software and safe operation procedures.

1. Physical Interaction Overview

The main object of the Crowdbot project is safe navigation of mobile robots in an environment with dense human crowds. In the past it is known that robots tend to freeze (i.e. remain idle) when further motion would cause collision. In Crowdbot we envision situations where human crowd density is high such that contact between robots and humans is no longer avoidable. Our goal is then to conceive adaptive robot navigation techniques that, in spite of the risk of contact and collision, will allow both humans and robots to coexist and share common spaces. Specifically, instead of the robot moving to minimize the risk of collision, we want to explore solutions that minimize the risk of injuries to humans that it comes in contact with. In summary, Crowdbot robots will invariably have physical contact with humans. The remaining issues to be addressed are: the types of contacts and the types of impact or force associated with each contact type. Collectively, such behaviors between a robot and a human and their corresponding scientific measures are known as physical interactions.

Our first focus in Crowdbot is to acquire knowledge of physical interactions between mobile robots and humans. Physical contact can be described as 1) touch (non-forceful interaction), 2) swipe (continuous touch), 3) force or collision (one-shot impact) and 4) drag (continuous force). For each physical contact, it can be further described as 1) head-on (face-to-face contact), 2) rear-end (contact from behind), 3) side-ways (impact at an angle), and 4) vertical (contact from top or bottom). For Crowdbot robots, we anticipate the first three types of contacts since human traffic flow is in parallel or at an angle to that of a robot's motion.

Our second focus in Crowdbot is the assessment of the severity (bodily injury) of different types of contacts on humans as exerted by a robot. What collision or pressure forces may occur in which situations and what forces can a human body (resp. specific body parts) tolerate without causing injuries? Details of both focus areas and our corresponding action plans are outlined in this report.

First, we describe the modeling paradigm: Various mathematical models are designed for the physical attributes of humans and robots plus their respective motion and interaction profiles such that we can develop a computer-based simulation tool that mimics physical interactions with a high degree of fidelity and under different environments and scenarios. Based on the results generated via such crowd simulation tool, we will be able to characterize and report on the risk of injuries to humans under various physical interaction scenarios. All required simulation-based models are detailed in Section 3. We also consider the modeling and analysis of worst-case scenarios where physical interaction is pushed to the extreme limit such as a fall (by a human or robot or both), domino-effect successive collisions, actions that cause severe injury and other scenarios caused by a robot malfunction.

Second, we provide a summary of empirical data via bibliographic study in Section 4: We evaluate work from related domains such as robot manipulation, biomechanics, automotive industry and sports sciences, where similar questions have been already studied. In particular, existing safety standards in these domains will be taken into account. From this knowledge, we will derive forces limitations that should give us bounds for physical interactions between robots and humans.

Third, we summarize two case studies of physical interactions: 1) the Pepper robot and humans in a socially interactive context in an indoor space and 2) a human-driven motorized wheelchair in an outdoor public open-space setting. Both cases are summarized in Section 5.

2. Modeling of Physical Interactions

This section summarizes mathematical equations and computer models to simulate physical interactions between a robot and human crowds. Indeed, in CROWDBOT, particular attention is given to collisions (both soft and hard) between humans and robots. The robot might be in a situation where the density is high enough that contacts are not avoidable anymore. Hence, the robot must decide to stop its motion —thereby becoming an obstacle to the crowd— or to move along with the flow or even move aside to clear the path for humans. In many situations, stopping the motion is not the safest option. In CROWDBOT, we consider that an evaluation of the risk of collision might be the key to develop safe navigation techniques.

If we allow the possibility of collisions, we have to deal with its consequences. The objective is to limit the resulting severity of the collision. To do so, we need to identify the theory and mathematical models that are useful to represent the consequences of a collision with a high degree of fidelity based on available data in related domains such as biomechanics and automotive industry. Also, to limit the resulting severity of the collision, we need tools that are based on such mathematical models such as computer-based simulations tools, industry standards metrics for collision detection and instrumentation for severity measurement.

This section of our report is organized as follow: Section 3.1 focuses on details of robot models, with a focus on realism and specifically for its physical (i.e. mechanical body) attributes. Section 3.2 deals with ways to simulate a human body with several levels of granularity based on tolerances to pressure and forces. Section 3.3 gives an overview of popular robotics simulation tools with a focus on their ability to handle physics-based model simulation. Section 3.4 describes motion models in the context of navigation with a robot on one side and humans on the other side, with both in motion. Section 3.5 deals with physical human-robot interaction (pHRI) and human-human physical interaction. The last section gives examples of worst-case scenarios that can occur when navigation fails or the robot malfunctions. Such events should be avoided and we provide simple recommendations to steer clear of such outcomes.

2.1 Robot Physical Attributes Modeling

In the context of CROWDBOT, there is a need to test out robotic scenarios (e.g. navigation, tracking) without running a real live test event with human participants. This option alleviates the need to deal with the consequences of collisions (personal injury) or monetary costs (physical or bodily damage) —thus beneficial from both operational and ethical perspectives. To avoid any risks of injuries due to collisions, a simulation tool that can model robot-human physical interaction is essential. This section explains how robots are usually simulated (industry practice), and what the limitations are of such models in terms of realism, modeling complexity and accuracy.

The first physical attribute of a robot is its kinematic chain. Robots are designed to perform specific tasks, in a specified environment. To perform its tasks, a robot is usually composed on several moving parts, called links, which are connected between each pair with joints.

The kinematic chain is a mathematical model of such structure. A link is considered as a non-deformable rigid body, and the joints are perfect (no friction) and they define constraints between links. In physics, the degree of freedom (DOF) of a mechanical system is the number of independent parameters that define its configuration. It is the number of parameters that determines the state of a physical system. For instance, a plane has six DOF: three translations in the space (up/down, forward/backward, left/right) and three orientations (yaw, pitch and roll), but an elevator only has one DOF, up and down, and the other DOF are subject to constraints.

Figure 1 gives an example of kinematics extracted from [26], representing the mathematical model of a planar arm with 3 links.

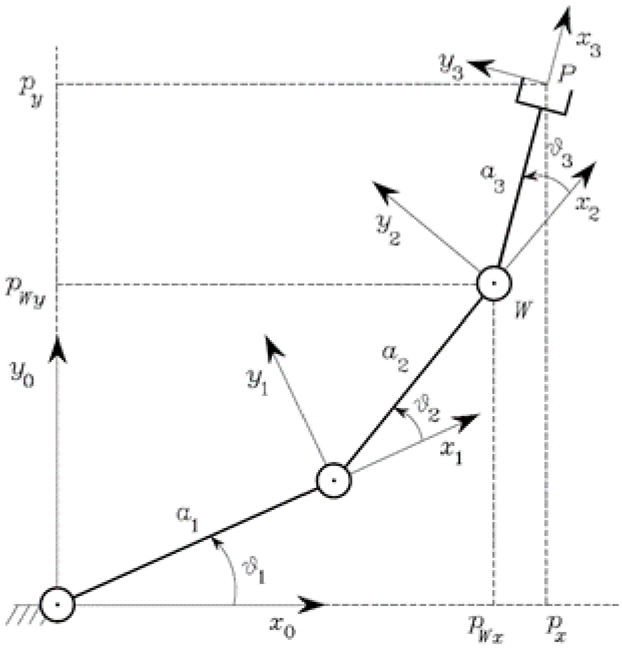


Figure 1: Kinematics of a typical robotics structure [26]

With a robot such as the autonomous wheelchair, the number of DOF is 3 because in a normal situation, the robot can control its movements on a floor which is simplified as a 2D plan (2 DOF), and only the yaw is controllable as a rotation (1 DOF). The wheelchair has 3 DOF, but only two are controllable: the forward velocity and the yaw —it cannot move sideways instantly. In contrast, the robot Pepper move its base in a different way: the number of controllable DOF of the base is equal to its total number of DOF. This means that it can move according to any DOF without any extra maneuvers. Also, Pepper the humanoid has 20 DOF in total, when considering not only the base, but the full robot motion of its head, limbs and body torso.

The inverse kinematics is the mathematical model of the ways a robot is able to move without constraints. It is the link between its configuration and its controls. Additional details about kinematics can be found in [25] chapter 5, and [26] chapter 2.

The second physical attribute of a robot is its shape and dimensions. The specifications have a huge impact on the structure of a robot. For instance, the robot Pepper's task is to create social interactions with people. It is an indoor robot designed to be aesthetically pleasant but it is not supposed carry heavy loads (< 500g) and move with high speed (5 km/h max). Due to such specifications, Pepper only weighs 28 kg with a low center of gravity for stability.

On the other hand, the purpose of an electric powered wheelchair is to carry someone, continuously, possibly for outdoor and daily use. Such system is necessarily heavily reinforced on its structure with steel channels and pipes. Appearance is less important so the shape is mostly the structure itself, and only batteries are hidden.

A 3D model has to be drawn when designing a robot. This model is the base of manufacturing plans on which tolerances are specified. This means that the 3D model itself is different from the real product, but usually, tolerances are small enough so this difference is negligible.

There are two common ways to define a 3D model of a surface. One way is by defining the surface with a mesh, which is a composition of small and simple shapes (triangles or rectangles). The smaller the pieces, the closest we get to the real shape. Figure 2 is an example of such mesh for the robot Pepper.

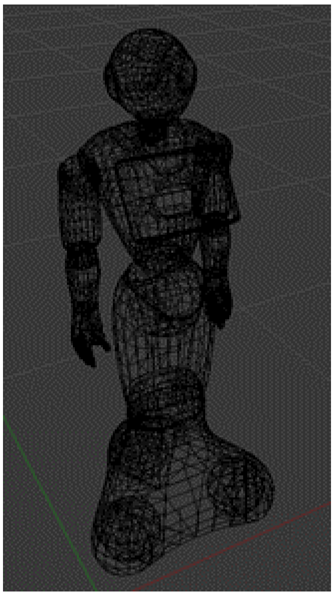


Figure 2: 3D mesh of Pepper in Blender

Another way to define a surface numerically is by the use of curves, which are influenced by weighted control points, such as B-splines, or non-uniform B-spline (NURBS). The curve follows the points and increasing the weight for a point will pull the curve closer to that point. The difference with the polygon mesh is that the points defining the surface are not physically meaningful but are control points. Traditionally, this is the way a surface is defined when drawing the robot on a computer. This is the most exact way to define the shape, because the surface is mathematically defined, while using a polygon mesh will always be an approximation, even with small elements. Figure 3 illustrate this approximation with a 3D model of a sphere.

Each link of a robot is usually considered to behave with a rigid body dynamics. When a force is applied on a rigid body, the deformation is non-existent and the distance between two given points of the rigid body remain constant.

Obviously, applying a force on an object, whatever the material, will create a deformation, even imperceptible. However, robots are usually design with a structure capable to support much more effort than necessary. For instance, a drag on a pipe of the wheelchair will barely deform it. Some polymers materials are easily deformable, but difficult to break, so they absorb a lot of Energy. Others are, on the contrary, will not have a perceptible deformation, and will break with a high energy impact. Since the purpose of such models is not the study of physical interaction in the first place, rigid body is really common because it simplifies a lot of things and allow to use mathematical models such as the inverse kinematic.

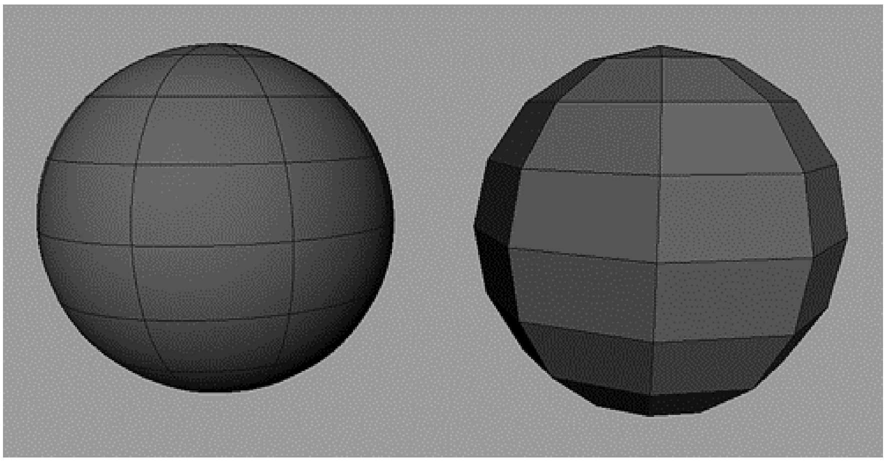


Figure 3: Comparison between two models of a sphere. left: NURBS, right: polygons

The rigid body approximation could be considered the worst-case approximation: if the materials are deformable, even a little, then a part of the energy is absorbed by the material itself, so the resulting energy after contact is less important than the one calculated with a rigid body. With this logic, a material that absorb a lot of energy during contact will limit the risks of injuries.

However, if the rigid body assumption is not realistic enough, a soft body simulation is the next step. The principles used for this kind of simulation is described in the section 9.

In a robotics simulator (see section 3.3), the virtual robot consider the independents links (e. g. a wheel of the wheelchair) as one set with physical attributes.

First, a visual representation defined by a 3D model, as explain just above, and some color or lightning feature.

Then, a rigid body will have parameters such as a mass at least, and inertial properties. A collider can be associated to the rigid body. A collider handle physics during contacts. A collider is defined with same kind of 3D model the visual is defined. When two colliders overlap each other, impulse forces are generated, as explained in [3].

A material can be associated to the rigid body. The material influence the contact behavior of the collider with parameters such as friction parameters and damping. The moving parts are connected with each other by defining a joint relation.

Of course, those parameters are only an estimation of the real robot and require fine tuning. Each one of these parameters are subjects to errors. Furthermore, with those parameters, we assume that each part of the robot behave according to the model of Newton for physics. The friction is usually modeled with Coulomb law, which is known to be a poor approximation.

However, the velocities considered in Crowdbot are slow enough so that a moderate difference between the reality and the simulation generated with those parameters is completely negligible.

In Section 3.3, we mention that robotics simulators use a physics engine. The physics engine is the software used by the collider to handle contacts, or by the rigid body to accurately react to forces.

In [4], the author compare different physics engines. Some tools are more efficient than others in a given simulation, while other tool perform better in another context. In conclusion, there is no perfect physics engine.

While some physics engines are able to generate soft body physics or fluid dynamics, robotics simulators only implement the rigid body physics capabilities of those physics engine. For example, for Gazebo, V-Rep and Webots, The soft body part and fluid dynamics part of the physics engine they use is always considered as feature that will come in the future, but not implemented yet.

Finally, a disadvantage of those models of the robot (kinematics, 3D model, physics engine parameters, collider...) is the fact that it is not possible to simulate as accurately as the reality itself. Internal or external factors are necessarily overlooked, and it is not possible to imagine every possible scenarios.

> "*The best material model of a cat is another, or preferably the same, cat.*" - Norbert Wiener & Arturo Rosenblueth (1945)

> "*World is its best model.*" - Rodney Brooks, 1990

Hence, a final validation with the actual robot in its actual environment is required.

2.2 Human Physical Attributes Modeling

The previous section addressed the subject of physical attributes of robot and we can model those attributes realistically. This section deals with the model development of physical attribute of the human body. With a robot, we consider the robot to be robust enough to resist to collisions with humans. With human, we focus more on their safety and how much they resist to physical interactions.

Even when we focus on mechanical properties, the human body remain complex, due to the variety in shapes, mass, sizes and physical conditions in the population. Organs differ in stiffness, in shapes, some are surrounded by fluids. For instance, a brain concussion happen due to a sudden acceleration, causing pressure waves to be generated, starting as a compressive wave at the site of impact and becoming a reflected tensile wave as it is reflected from the skull at the opposite side, as described in [6].

There are many different kind of injuries, with many possible causes. For instance, the cause of an acute subdural hematoma, a form of hematoma associated with traumatic brain injury, is still a subject to debate (see in [6]).

Because of its complexity, the human body is difficult to model. A robot is made of simple, well-defined structures. The materials used have known physical properties. This is not the case for a human body and the model development of a human body is most of the time subject to drastic simplifications, especially when the physical accuracy is a secondary issue, for instance in crowd simulation.

One of the simplest human representation is the one used by the crowd simulation community. There are two major way of doing crowd simulation. One way is macroscopic crowd simulation, which models the crowd as an active continuous matter, and computes the variations of density in space and time to estimate the motion of the crowd. In this representation, the representation a particular human in the crowd is undefined.

The other way is microscopic crowd simulation. In this representation, we define an agent that is a simplified representation of a human, with its own control law, and simplified mechanical properties. The crowd is then composed of multiple agents, and collective behaviors emerge from individuals interactions.

Due to the high number of agents, the definition of a single agent has to remain simple.

Most of the time, when doing microscopic crowd simulation, we don't bother with collisions because, as in the field robotics, navigation strategies are considered collision free.

The popular representation is then minimalist: the crowd moves in a 2D world and an agent is represented with a rigid circle. Collisions are handled to avoid superimposition of agents, but they are not physically accurate.

Some researcher in the crowd simulation community tried to change a bit the shape of the agents, for example with 2D ellipses in [7] or 2D capsules in [8]. Those representation is closer to an actual human body. However, the focus is on the way this agent should be oriented, to study behaviors like side stepping.

Another model of an agent is based on footstep representation [9]. The idea is to generate footsteps as the output of navigation. An inverted pendulum represent the agent, and the footsteps are computed according to a new desired state for the center of mass.

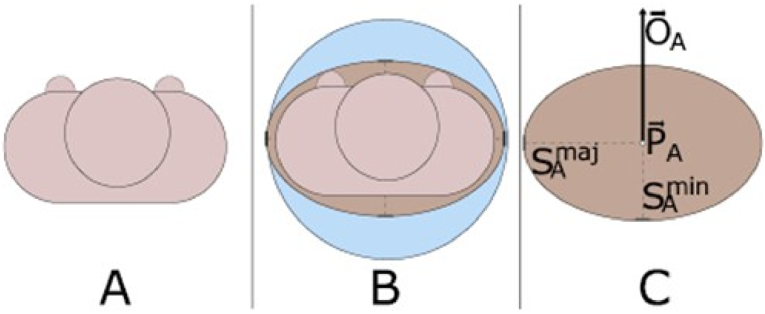
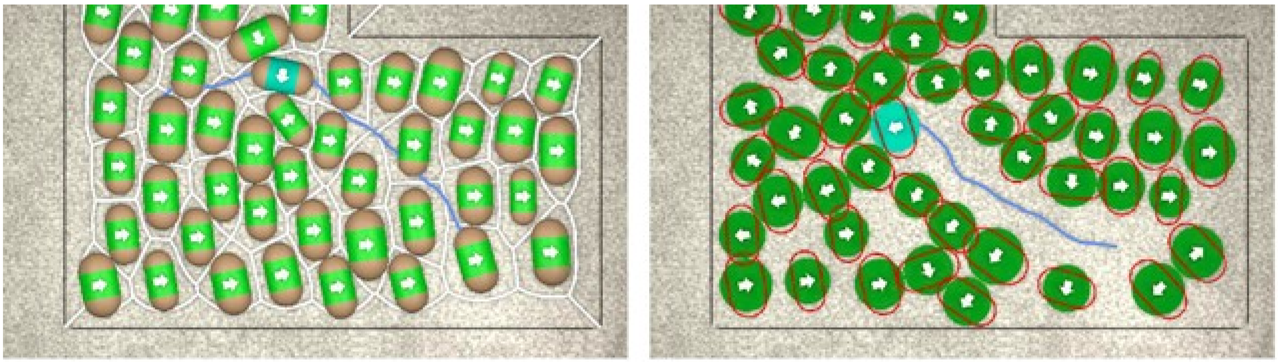


Figure 4: Representation of agents in [7]



(a) *Torso Crowd finds a path to the goal.*

(b) *RVO with the smaller agents, with the same surface area as the capsules, does not find a path to the goal.*

Figure 5: Representation of agents in [8]

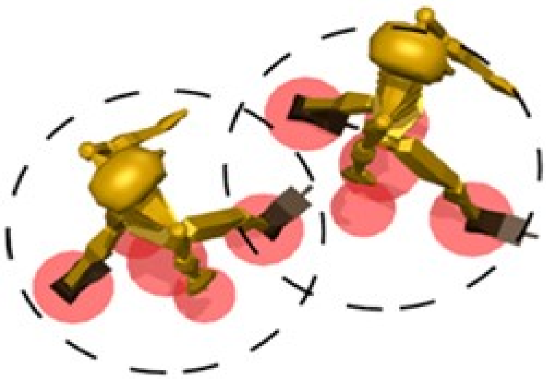


Figure 6: Representation of agents in [9]

While those models are interesting for computation reason, they are not designed to deal with the problem of accurately representing a collision during interactions.

However, the field of injury biomechanics study the risks and causes of injuries of human body. In this field, a lot of misinformation need to be clarified. As said before, there are divergence in opinions at the medical level about the origin of some specific injuries [6].

Despite those debates, there are standards coming from the science of car accidents. Car manufacturers and military laboratories invested in those field. Many experiences have been done on cadavers to study the mechanical properties of the human body, such as inertial properties or stiffness of the limbs.

Diverse diagrams exist in the literature ([6], [10], [11]), for instance some give you the probability curve of foot-ankle injury depending on the force you apply on it, as in the figures 7, 8 and 9.

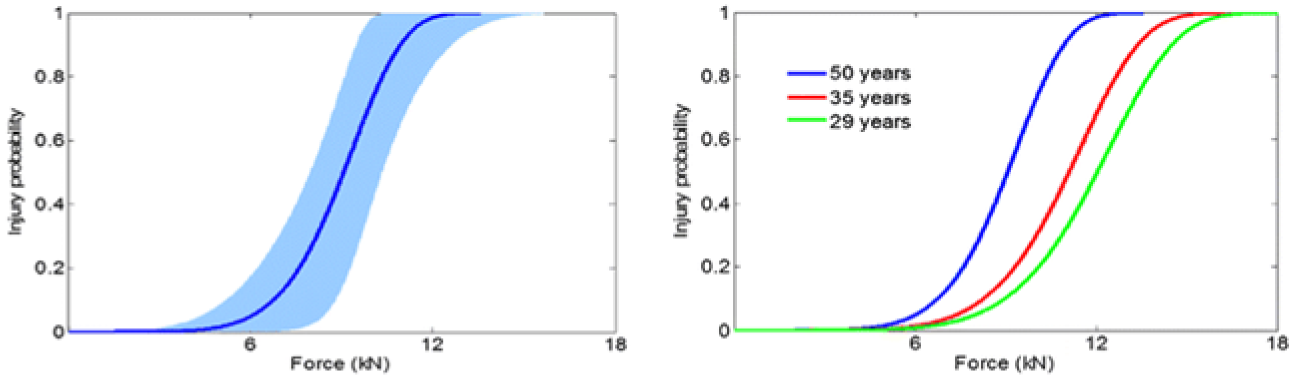


Figure 7: Probability of injury for a given force, [10]

Thanks to this kind of preliminary study, car manufacturers are now able to validate their crash tests using a dummy replicating the mechanical properties of a human body, for example in figure 10.The major problem when using a dummy is the cost. A single crash test is expensive, and a proper statistic study needs a multitude of crash tests. With the power of computers nowadays, efforts are being made in the direction of simulation tools.

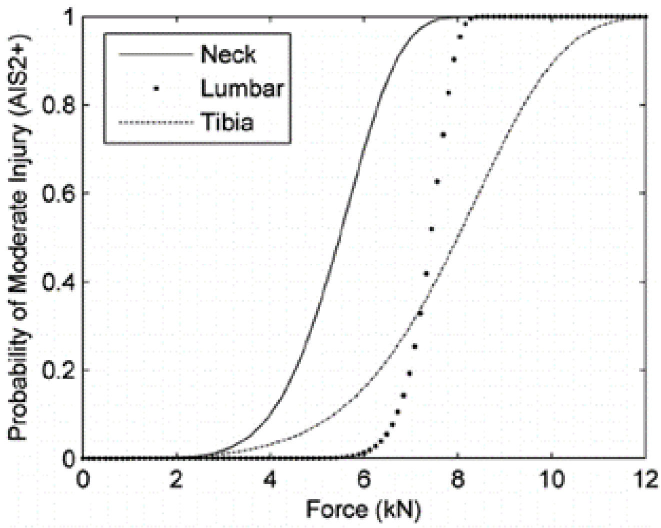


Figure 8: Probability curves in [11]

In Crowdbot, we need a simulation tool to evaluate the risks. The models presented so far results from analysis of experimental data, or do not represent contacts accurately. We can use equation of the distribution of stresses to be more physically accurate. Those equations are known, but they cannot be directly solved on a complicated shape such as a human body. However, it can be solved for very simple shapes like a triangle or rectangle, as shown in figure 11. Thus, this section presents soft body physics, or how to deform a 3D model.

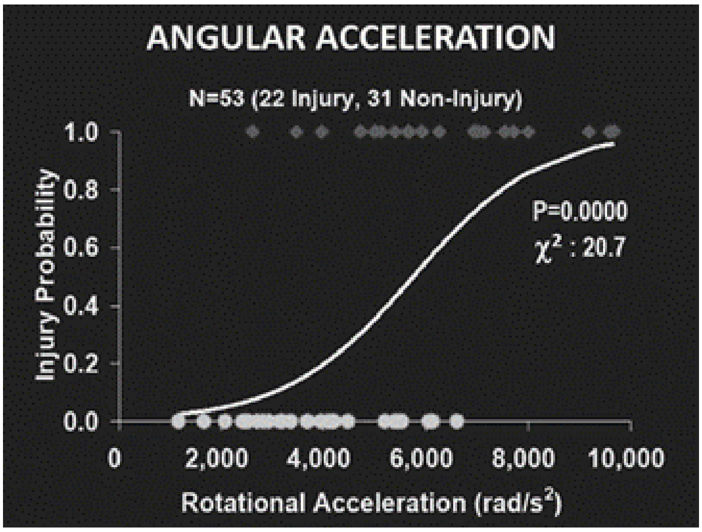


Figure 9: Probability curve in [6]

Soft body physics take advantage of this simplification and replace the complicated shape with an approximately equivalent network of simple element, the finite elements mesh. The simulation accuracy is high with small elements, but the computation time increase with the number of elements in the mesh.

Figure 10: Hybrid III dummy

This kind of method require doing a lot of calculations, but the results are close to the reality. An example of such method is the spring/mass model. Each point of the mesh, the nodes, are modeled as point-mass and the connections between the nodes are modeled as perfect springs obeying Hooke’s law. Applying Newton’s law on those point-mass then gives a system of differential equations.

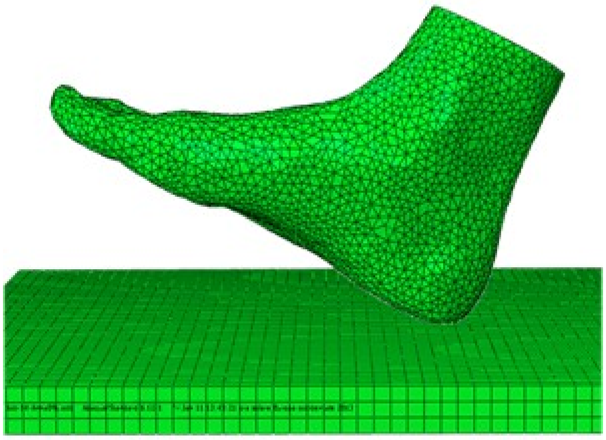


Figure 11: Finite element method applied on a foot

The framework SOFA (https://www.sofa-framework.org/) is an example of application of finite elements for medicine purpose.

In [25] chapter 9, animation of the human body is discussed. In particular, the way the nodes of the mesh are connected to the kinematics links so that the mesh deforms itself, following the movement of the links, to represent muscles contraction. The whole chapter 9 in [25] is dedicated to human animation, and the techniques described in this book are close to the one we can use in structural analysis.

Finally, a promising technique is the iso-geometric analysis (IGA). Even though the idea is old, the first paper about this technique was published in 2005 ([27]), while finite element method (FEM) appeared in the years between 1950 and 1960. This technique use a mathematical 3D model based on curves, such as B-spline, or NURBS. Computer assisted design (CAD) is more recent than FEM (1970) and modeling a surface with splines appeared with it. Iso-geometric analysis use the representation of CAD for 3D models. This technique simplify the mesh refinement, which is the main bottleneck in finite element method, reducing the computation time drastically. The approximation is better with this technique, and the results are smoother, thanks to the spline representation.

IGA is a recent method and still under development, thus the classical FEM is the most used today.

2.3 Robotics Simulators

This section present existing tools that simulate a robot. A robotics simulator is a software that allow to create applications for robots without using the actual robot or the actual environment. For instance, in the industry, a robot arm dedicated to pick and place, machining, or painting tasks can be programmed in a robotics simulator. Such robots work in a controlled area so the simulation environment is minimalist, with the robot itself and the product its working on. Programming such applications require a visualization of the robot doing its task. A simulator is perfect for the conception of such programs. Figure 12 shows a simulation of a pick and place delta robots with a professional simulator dedicated to industry, visual component.

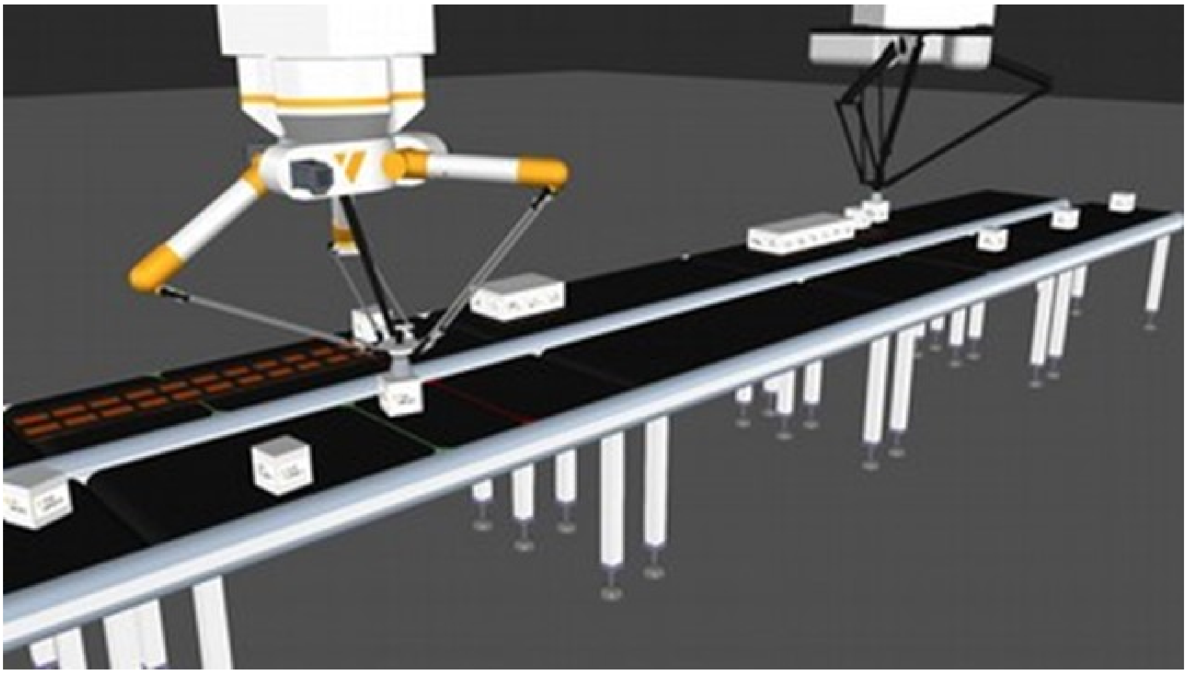


Figure 12: Application example of robotics simulators: pick and place program for delta robots using Visual Component software

To give another example, some robotics simulators, such as gazebo, are suitable for mobile robotics. Such tool allow robotics engineers to try their navigation algorithm or to add additional sensors easily, in a controlled environment. Such tool allow the validation of prototypes. The figure 13 shows the mobile robot ROSbot 2.0 simulated in Gazebo, equipped with a simulated LIDAR (planar range sensor).

Those examples of application shows that robotics simulators are useful to demonstrate robot capabilities at early stage of their conception. It is generally a great tool to validate new designs of robots, or new features in an existing robot, like additional sensors or new algorithms.

Popular robotics simulators represent the robot and its environment in 3D, as showed in figure 14. The virtual robot reproduce the way the real robot interact with its environment. Hence, testing or debugging programs can be done easily and quickly at the early stage of development without the need of the actual robot.

A standard way to control robots is ROS, which is depicted in figure 15. This framework provide a standard messaging infrastructure, an extensive set of tools configuring, starting, debugging, visualizing, logging, testing your application. ROS has a collection of libraries that implement useful robot functionality. Finally, A large community contribute to ROS.

Popular features of simulators is the fact that the virtual robot has the exact same inputs as the real one. That mean it is possible to test directly the algorithms with the same interface, for instance with ROS. This integration is already a source of error between the virtual robot and the real one.

The real time factor of the simulation is crucial here. In the contrary, the real robot might experience small delay in its internal communication that is not taken into account in simulation.

Some robotics simulators are dedicated to a specific area or set of robots: cheap robots for education, production line in industry, or industrial robots in general. Others are more general.

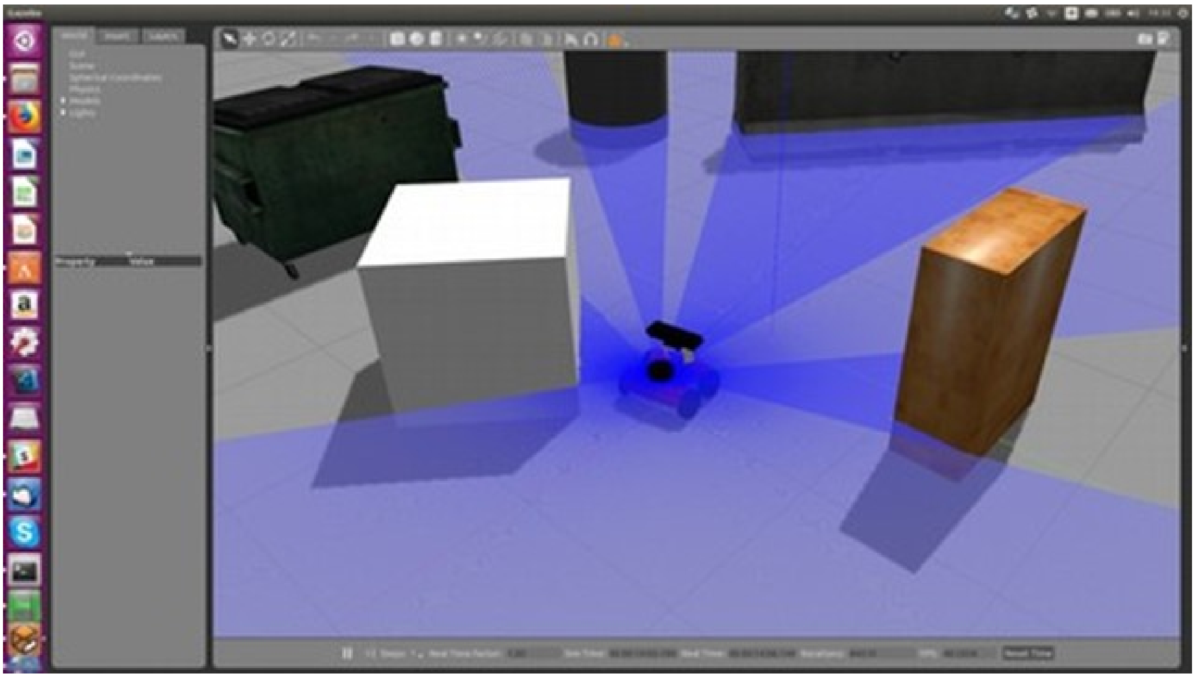


Figure 13: Application example of robotics simulators: Validation of navigation techniques for simulated ROSbot 2.0 mobile robot using Gazebo software

Among the long list of simulators claiming their superiority in some way, some are more suitable than other. Simulators like V-REP or Gazebo are well known in the community. While the first can be better in a given configuration considering metrics like CPU usage in [1] and is more user friendly, the second is the preferred simulation when working with ROS.

The main drawback with V-REP is that it is a commercial tool (with an educational free version), while Gazebo is a fully free, open-source project.

Another concurrent to Gazebo is the MORSE simulator. While its performances are better in a given context in [2], it is a relatively new project with a small community, compared to Gazebo.

Most of the time, robotics simulators comes with a physics engine that provide an approximate simulation of physical interactions. With such software, it is possible to simulate rigid body dynamics and compute forces, define inertia, compute collision detection, or define drag, stiffness, and damping. [3] is a good starting point to understand the basics about rigid body simulation. Today, robotics simulators implement only the rigid body capability of their physics engine. Unfortunately, the soft body simulation interface is not supported yet for any of the presented robotics simulators.

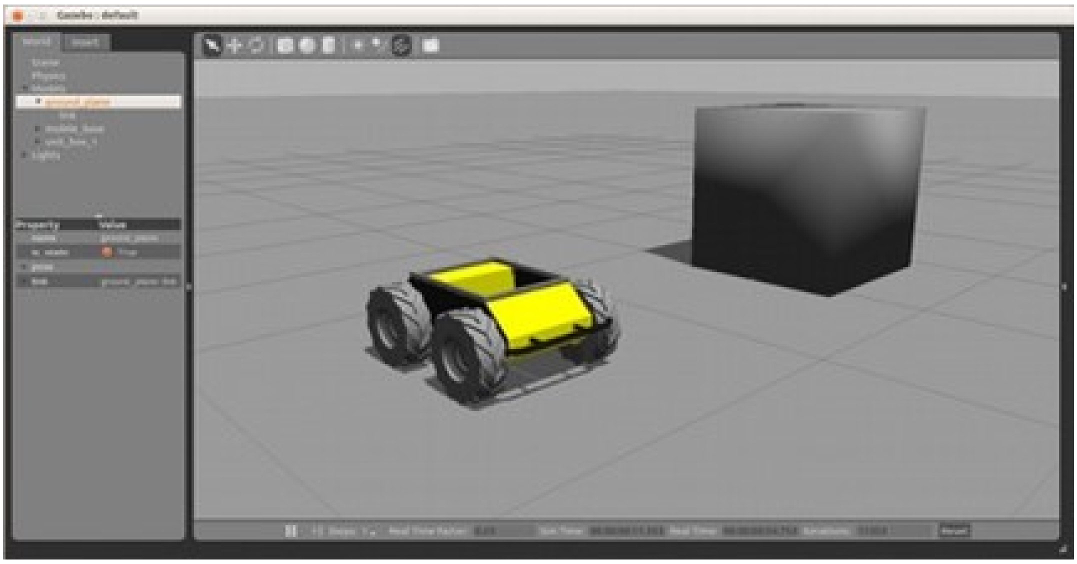


Figure 14: Husky robot simulated in Gazebo

Regarding robot simulation, many tools exists, the paper [5] compare some of those based on user experience. The conclusion of [5] is that Gazebo is the best open source candidate for robotics simulation involving multiple contacts, thanks to its active community and support, and mostly for its extensive list of supported physics engines. V-Rep is the best commercial tool, for the same reasons. But the most important conclusion of this paper is that there are plenty of different simulators, but none is perfect, and researchers should concentrate their effort on common open-source.

Things changed a little since the publication of [5]. For instance, the open source middleware ROS used to be a minor tool in robotics in 2014, while today, it is a well-known standard. In the contrary, small tools disappeared. However, there is still a need to converge on a robotics simulator.

Due to the extensive list of tools existing today, we only reference the most used tools. Some of them, such as Actin, RoboDK or OpenRave, are more suitable for industrial robots. Some projects are not listed in the table the various reasons. Some are too simple, for instance S.T.D.R. Simulator which is a 2D simulator. For many tools, the developers have stopped maintaining it, for example Microsoft Robotics Developer Studio (MRDS), or ARS. Others projects are too small to be interesting enough for us, such as SimsSpark. This kind of simulators are maintained by small groups and suffer from a lack of features, community, or optimization.

Regarding the models and tools discussed in the previous chapters, only a few applications consider the collisions, and its consequences. Many tools are great to solve classical problems such as motion planning or collision avoidance. However, since the consequences of collisions is an unexplored path, current tool are not adapted yet to solve those problems. However, it is a good starting point.

Figure 15: the ROS equation

The software architecture of Crowdbot have been built based on ROS. For this reason, a relevant robotics simulator for the project should have an integration with ROS. The robotics simulator should be free and open source. The simulation should be feasible with limited hardware resources (laptop). Finally, It should use an accurate representation of the robot and the world: the physics engine should be accurate, as well as the sensors simulation. Next section describe what kind of models are mostly used, and the notion of realism with respect to physical attributes is being discussed.

2.4 Motion Profiles

In [12], S. Thrun states that the robot motion is subject to errors, and the controls alone are therefore insufficient to determine a robot's pose (location and orientation) relative to its environment. The noise in the system is a key problem for robot navigation.

In the literature of robotics, the motion model has a precise definition: it is the link between the command and the final movement. In [13], it describes the posterior distribution over kinematics states that a robots assumes when executing a motion command starting from a given pose. It means that the current kinematic state of the robot can only be estimated, with the previous kinematic state and the last command executed, as shown in Figure 16.

For instance, robots like an autonomous wheelchair can use the velocity motion model described in [13]. Pepper robot base is a holonomic system, this mean that it can move in any instantaneously without additional maneuvers. For instance, Pepper robot can move sideways, while the wheelchair has to turn and then move forward. A robot is holonomic if the number of controllable degree of freedom (DOF) is equal to the total number of DOF: the wheelchair is free to move on a planar surface (2 dimensions) without constraints on its orientation (1 dimension), so has 3 degrees of freedom, but can only control its rotational speed and linear speed.

Those robots are different but the link between inputs (controllable DOF) and output (position and orientation of the base) is calculable, and is called inverse kinematic. For pepper, the output might be the position of the hands. The link between the base and the hand has to be calculated the same way.

When it comes to human body, the opposite approach is taken. Motion models are built from analyzing human movement. The field of movement analysis try to define with what kind a control law humans steer themselves.

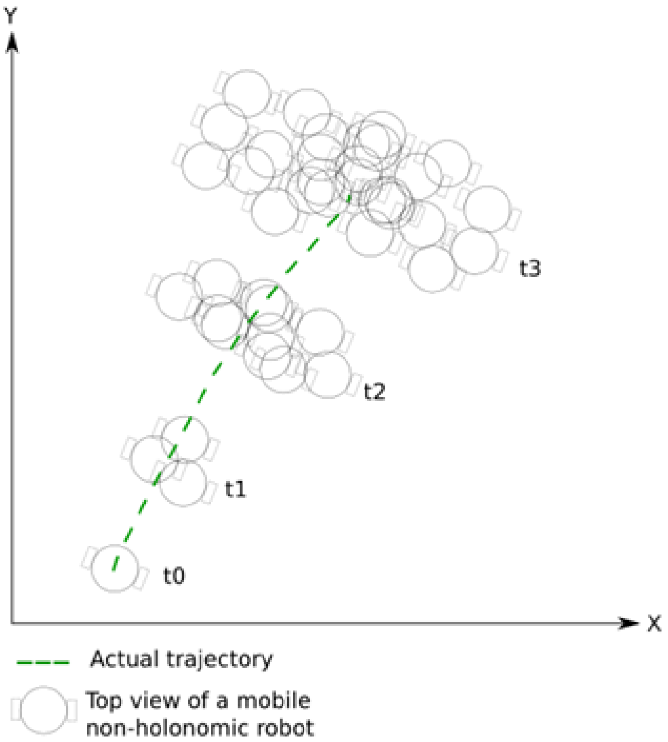


Figure 16: Robot motion model

The analysis of the results of [14] suggest the trajectories minimize the derivative of the curvature of the path, as shown in figure 17. The paper describes an experiment where subjects are asked to walk within a motion capture facility from a fixed starting point and direction, and to cross over distant porches for which both position and direction in the room were changed over trials.

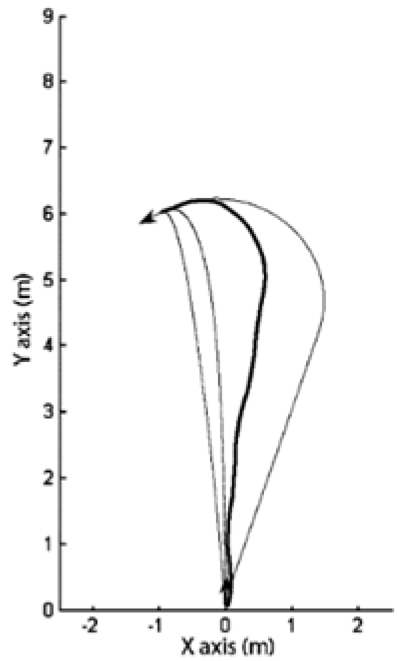
In [15], another analysis of human movement suggest the motions of the feet are organized around the center of mass.

Another aspect of human motion is the anticipation of the gaze and the head orientation toward the future trajectories, as shown in [16].

Finally, the head motion seems to be a combination of stabilization of the gaze and anticipation of the future path, as suggested in [17].

The common point between human and robots, is that they move in the same environment. Human are holonomic systems. Like robots, their speed can be measured. An evaluation of their position and motion is possible. This is the core problem of crowd simulation and pedestrian tracking. However, the subject of motion estimation is beyond this report.

Finally, a holonomic robot is probably more suitable in a crowd, since it is capable of moving in every direction instantly, joining or leaving the crowd without extra maneuver, or react to the crowd flow, which is hardly the case with non-holonomic robots.



Among four "possible" trajectories reaching the same goal, the subject has chosen the bold one. Why?

Figure 17: Optimal curvature principle from [14]

2.5 Interaction Profiles

Human-robot interaction (HRI) is a multidisciplinary field at the border of robotics, ergonomics, and psychology. In this sub chapter, focus will be on the physical aspect (pHRI).

PHRI issues are listed in [18], as well as design recommendations and standards.

The question of safety is directly linked to the type of injuries the machine can cause. As said in the sub chapter 3.2, car manufacturers are the most advanced in terms of safety. They designed severity indices (AIS figure 18), and others standards like HIC for head injuries. As said in [18], current standards for robot safety in factory are lacking when human and robot share the same environment. Car manufacturer standards can be a starting point for robot safety standards.

Injury	Score
Minor	1
Moderate	2
Serious	3
Severe	4
Critical	5
Unsurvival	6

Figure 18: AIS injury scale

To be safe, robots designers must think of a safe structure, without sharp edges, with lightweight but stiff materials, and compliance (soft and absorbent covering, compliant joints). Also, dependability of the system has a big impact on safety. In a simulation, robots models are perfect and a physical simulation is imperfect: An impact between a human and a robot could be underestimated due to a dangerous design of the robot, and a bad dependability.

Moreover, in [18], active safety is also discussed, such as impedance control, as well as the real time aspects.

When a robot is safe in its structure, the interaction model can be simplified. For instance, in [19], the focus is on drone safety: the author simplify the human and the drone model, and use kinetic energy, to finally define a safety criterion which is a mass threshold.

Another complex aspect of the interaction is the crowd itself. The field of crowd simulation focus on macroscopic properties like density or crowd flow, or microscopic control law based on goal reaching or collision avoidance for individual agents. However, only a few papers consider the collisions between agents.

When the density is so high that individuals are not completely free to move, contacts are inevitable, so simulations with collision avoidance fail to be realistic. Due to ethical reasons, it is difficult to gather data of high-density crowds. When it is possible to analyze such data, the study mainly focus on global, macroscopic properties and behaviors, such as waves in the crowd, for example in [20].

If we want to get closer to physical interaction between individuals, we can consider the analysis of density peaks, which is the main cause of injuries in high-density. All crowd death are, eventually, caused by asphyxia [21]. There is a point where the force from the waves is so high that people cannot resist, and can easily fall down. Then, people can stack up vertically, so that individuals at the bottom experience a high pressure. In the literature, most consider that in a density of around 7 people per meter square (the value can vary between references), individuals are not free to move anymore and the crowd can be considered as a fluid.

Finally, a few attempts of combining collisions avoidance and pushing behavior in crowd simulation, using simple models, like in [22], [23] or [24].

If we want to define interaction more precisely, we can describe the different types of interactions on three scales: the force, the duration of contact, and the relative motion direction of agents in contact. If the force is negligible, then the interaction can be a simple contact, or a swipe, depending on the duration of the contact. In the contrary, if the force is big, the contact can be an impact or a drag.

The relative motion direction of colliding agents can be head-on, rear-end, or side-ways. Depending on the compliance of the robot, or the fragile points of the human body, this factor influence the risk of injuries.

Finally, the severity of each interaction can be measured using the AIS scale in figure 18. Evaluating the severity can be done with multiple levels of fidelity. First, a subjective feedback of human participants experiencing actual interactions with robot. Another method could be based on sensors data collection during an interaction experiment, where the severity is estimated after analysis. Finally, using simulation, the human-robot interaction could be approximated, and the severity could be estimated using previously described models of human body.

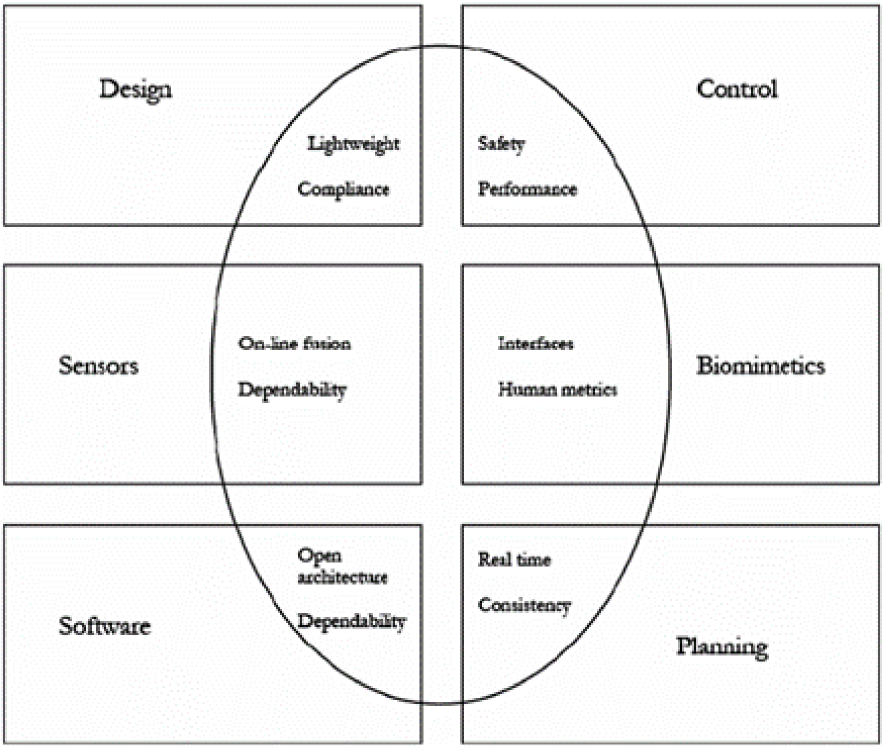


Figure 19: pHRI is a multi-disciplinary problem

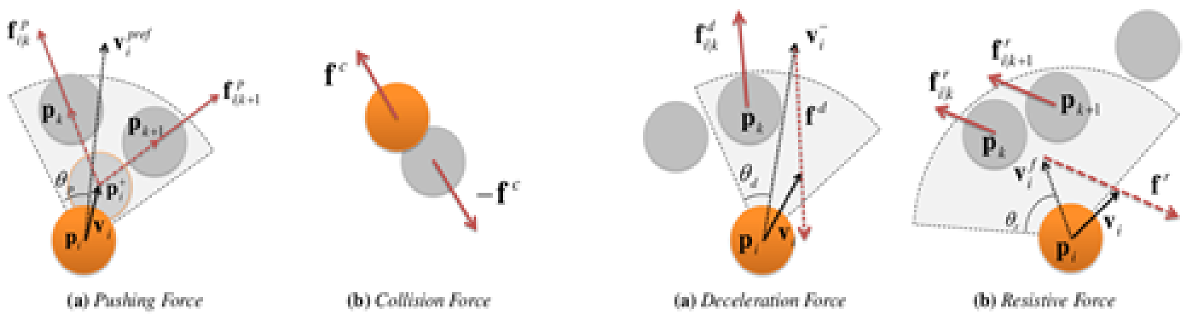


Figure 20: Pushing behavior combined with RVO in [22]

2.6 Worst-Case Scenarios

To conclude this chapter let's try to imagine the worst case scenarios. To do so, a list of the main causes of injuries in interactions is needed.

First, if the mechanical design is full of sharp edges, then the risk of injury becomes high, whatever the scenario. Sharp edges concentrate stress locally, while a smooth design distribute it, allow a better absorption of the stress. Additional soft covering with shock absorbent material highly reduce the risk of injuries.

Another example is with non-compliant robots. Even with an absorbent design, a robot in a dense crowd might be subject to continuous forces from the crowd. If the root is non-compliant, individuals applying continuous forces might lose their equilibrium and fall.

The dependability of the robot is important too. For instance, a robot that can fall down might have unexpected behavior, and can be dangerous for people in the crowd. A low center of gravity then recommended. The dependability also means that the robot is acting in real time. If this is not the case, an absence of reaction or a late reaction to an event might surprise the crowd with unexpected behaviors. It also mean that the robot will not suddenly move at maximum speed without control, for instance in case of malfunction.

But, even in small density, and considering a compliant and dependable robot, an important factor of injuries is the kinetic energy. Injuries are cause by transmission of energy. Kinetic energy is proportional to the mass. A heavy robot is a source of problems in a crowd: a bigger effort is needed for them to move. The other component of kinetic energy is the squared relative speed. A high speed, even with lightweight, soft and compliant robot, is susceptible to transmit high amount of energy during contacts. Clamping the speed for a given mass is a relevant safety measure. Since it is the relative speed that is important, in cases where directional flows are distinguishable, a robot moving in a different direction from the crowd direction present a risk.

Even with low kinetic energy, a robot capable to transmit high force/torque might be dangerous. Such robots can generate bigger forces than humans are capable to resist to. This is a problem if, for instance, the robot fail to detect individuals in its path and continue to push no matter what. While the impact force is minimal, a continuous force with high magnitude might result in serious injuries.

Finally, the worst-case scenarios would be the chaotic situations where one of the agents, the robot or humans in the crowd, lose control and/or fall down. Chaotic scenarios are difficult to simulate by nature. A human that is losing control will try to recover by all means, for example by grabbing or pushing. If a human or a robot falls, it will create an unexpected situation that is impossible to predict, due to the butterfly effect. The fall of a human can be caused by a contact with the robot with enough force, and can be the cause of the fall of other humans in the crowd. This scenario is really dangerous in very high density. However, it is less likely to happen with the density levels considered in Crowdbot. Indeed, we consider that humans are still capable to move freely and can react without too much constraints.

For the robots considered in Crowdbot, it is hard to make them fall down thanks to a low center of gravity. If they do fall on a human, then the gravity of the impact will be limited.

The problem here is that people recover their loss of equilibrium in an unexpected way. If they cannot recover, the fall itself is dangerous, especially for elderly.

If the robot has a shape so that the contact area during a collision is far from the center is far from the center of gravity of the person, for instance near the knees or the head, then the risk of loss of equilibrium is high. In the contrary, if the contact point if close to the center of gravity for example between the waist and the torso, then it is easier for the person to keep its equilibrium. The drawback with a contact near the center of gravity is that the person will have to absorb all the energy quickly, increasing the risk of injury at contact.

3. Bibliographic Study of Physical Interactions

Physical interaction, in particular physical Human-Robot-Interaction (pHRI), has been reviewed by several authors, often with an emphasis on safety, risks and dependability issues. Some older surveys with such an emphasis are [1 Alami 2006] from 2006, [in your Deliv. ref #18 Santis 2008 Atlas)] and [2 Pervez 2008] both from 2008. All of them include a high number of related literature until that time and try to structure the domain of pHRI in different ways. [3 Bicchi 2008] gives an overview on safe physical interaction with highlighting ongoing standards activities and classifying pHRI into hands-off and hands-on pHRI systems.

[4 Argali 2010] focusses on tactile interaction. Existing approaches are classified according to the sensors used as well as to the type of interaction. In a recent work [5 Guiochet, 2017] dependability techniques are investigated where human-robot closeness and human-robot interaction are considered as two properties of robotics systems. The paper [6 Khan 2014] gives an overview of compliance control methods to achieve safe pHRI.

In addition several surveys present HRI on a more general level where physical interaction is only one aspect amongst others. In [7 Goodrich 2007] a main distinction is made between “remote interaction” and “proximate interaction”, where proximate may, but not necessarily has to, include physical contact.

The more recent paper [8 Lasota 2014] from 2014 defines the term “physical safety” and divides safety methods into four main categories (safety through control, through motion planning, through prediction, and through consideration of psychological factors). Physical interaction is in particular relevant in the first category, which itself is divided into pre- and post-collision methods. [9 Vasic 2013] presents an overview on safety issues ranging from industrial robots over mobile robots to assistive robots. [10 Sheridan 2016] divides HRI into four main application areas, where physical interaction would be mainly relevant only in the fourth area that is related to social interaction.

The above listed references all have the characteristics of survey papers, giving structure to the field under consideration and providing a large number of references, including those were actual physical interactions have taken place.

A field that is only partially covered in above papers is robot navigation, although research on navigation in human-populated environments has gained a lot of attention in the last years. A survey in [11 Kruse 2013] considers interactions as results from navigation. But similar to classical robot path planning, the vast majority of approaches try to avoid collisions, with various additional constraints such as maximizing a user's comfort, naturalness of behavior, etc. Interaction mostly happens by influencing the motion paths of the robot, or e.g. by keeping certain distances between robots and humans. In most cases robots do not move during the direct physical interaction, e.g. while the human communicates via speech or a GUI to the robot.

Some noteworthy early examples where robots have demonstrated such human-robot interaction in practice include Rhino [12 Burgard 1999] and Minerva [13 Thrun 2000] for museum guide robots and [14 Prassler 1999] for a Robotic wheel chair.

For some types of robotic devices, physical interaction is the primary method of control. This holds for self-balancing personal transporters like Segways [15 Nguyen 2004] and Hoverboards [16 online], where appropriate control algorithms react quickly to the changing weight load from the user. Several studies have investigated injuries caused by such devices [17 Boniface 2011], [18 Siracuse 2018].

Another special kind are supportive devices such as exoskeletons [19 Anam 2012] which amplify or compensate the forces of the user. For humanoid and self-balancing robots control schemes have been developed to let the robots counteract physical impacts. Some of the most sophisticated examples of robots of this kind were developed at the company Boston Dynamics [20 Kuindersma 2016].

Small consumer or toy robots such as domestic vacuum cleaners also allow direct physical contact due to the low weight and low power of the devices.

3.1 Robot Manipulation

Industrial robot manipulators usually have to handle large weights, requiring high forces and powers. Therefore they pose particular danger to any human in their vicinity and have motivated researchers for a long time to find ways to handle these risks and to enable direct interaction between manipulators and humans. This becomes more and more important with the introduction of Industry 4.0, human-robot collaboration and manipulators for service applications.

Very relevant in this field is the work from Sami Haddadin [21, 22]. Some of his results have been used in the definition of current ISO norms for the safety of robots.

[23 Haddadin 2009] presents a systematic evaluation of safety in HRI. Using standard automobile crash test facilities, several industrial robots of different weights have been evaluated. Also the influence of the mass and the velocity of the robot was investigated. Human injuries are discussed from different perspectives and with tests on human body parts (chest, head, abdomen and shoulder), leading to the classification of different possible injuries relevant in robotics.

[24 Haddadin 2011] investigates sharp contact injury in human robot interaction and discusses about the biomechanics of soft tissue, depth of vital organs, minimum braking distance, collision detection and reaction, together with experimental results.

The safety map concept has been proposed in [25 Mansfeld 2018] in order to analyze the safety performance of a robot. Experimental results for a pick and place robot have been presented for evaluating the safety and task performance of the concept.

3.2 Standards and Regulations

Existing regulations for robots in the European Union comprise on the highest level the Machinery Directive 2006/42/EG [26 Machinery] as well as several international norms, including ISO 12100 [27 ISO] for general principles of safety of machinery, ISO 13849 [28 ISO] for safety related parts of control systems and IEC 62061 [29 IEC] for functional safety of control systems, including the definition of safety integrity levels (SIL).

ISO 10218 [30 ISO] defines safety requirements for industrial robots. It describes general methods to achieve safety during physical interaction, such as limiting power and forces.

ISO/TS 15066 [31 ISO] was introduced in 2016 to define more precisely the safety requirements for collaborative robots, still with the focus on industrial robots. It specifies tolerable levels of force and pressure for different body parts during a collision.

Similar safety recommendations of force limits on different body parts have been already published in 2009 (revised in 2011) by the BG/BGIA [32 BG].

A study report [33 HSE 2012] analyzed the validity of the force limits in the draft of ISO 15066 and came to the conclusion that, in spite of the large number of sources that were used for the definition of the values, their validity is hard to assess due to remaining gaps in research and ethical issues. It lists a number of considerations that eventually should be taken into account and may not be adequately handled in ISO 15066.

ISO 13482 [34 ISO] (published 2014) defines safety requirements for personal care robots, covering mobile service robots, physical assistant robots and person carrier robots. Concerning allowed contact forces it requests a risk assessment to be carried out, but defers to other standards in order to determine concrete limits. This standard as well as ISO/TS 15066 include a number of references which investigated impact forces and injury consequences.

3.3 Automotive Industry

In the automotive industry, where impacts with vehicles can have deadly consequences, instead of physical interaction the higher concerns are possible injuries that can result from such impacts. Therefore the classification of injuries has been standardized, which is still mostly lacking in the robotics domain.

The Abbreviated Injury Scale (AIS) [35 Gennarelli 2008], created by the Association for the Advancement of Automotive Medicine (AAAM), is currently the most widely used injury scaling system in automotive industry. In AIS injuries are classified according to the injured body region (head, spine, etc.), anatomic structure (vessels, organs, etc.) along with some details and the severity of the injury. In the case where multiple body parts are injured, the injury with the highest severity rating becomes the overall injury severity, called Maximum Abbreviated Injury Scale (MAIS) [36 Barnes 2009]. AIS is only a classification system, but no injury severity index, as it does not provide the criteria to determine the severity of an injury.

A commonly used head-injury severity index in automotive industry is the Head Injury Criterion (HIC) [37 Versace 1971]. HIC is based on the Wayne State Tolerance Curve (WSTC) [38 Namjoshi 2013], which indicates the likelihood of a head injury in the event of sudden deceleration. This index is for example used by the Insurance institute for Highway Safety to evaluate vehicle safety ratings [39 online].

Impacts on the neck area are generally assessed according to the area of impact, which is the front and rear side of the neck. This separation is needed since impacts on the front and rear side of the neck would have different consequences to the affected person. Some examples of neck injury severity indexes are the Neck Injury Criterion (NIC) and Intervertebral Neck Injury Criterion (IV-NIC) [40 Panjabi 2005]. [1 Alami 2006] mentions that for torso injuries there are considerable amount of injury severity indexes available which can be categorized according to the origin or cause of the injury (acceleration, force, compression and soft tissue).

Injury severity scoring systems that are used in the aforementioned injury severity indexes usually do not directly or linearly correspond to AIS injury severity grading system. They are often in the form of a limit that separates between severe and non-severe injury. Therefore, some conversion needs to be applied to the score before the MAIS severity level can be determined.

4. Physical Interaction Case Studies

Physical interactions between human and CROWDBOT robots such as the smart wheelchair and the Pepper humanoid are a key point when the platform is deployed in a crowded environment. Work Package 3 (WP3) focuses on reactive navigation and the content of this section is relevant for the design approach in order to assess risks in the scenarios proposed in WP1. Analyzing the current baseline in similar scenarios can help to anticipate issues and design experimental setup accordingly as well as serving as a basis for modelling interaction in the simulation platform (T4.2 & T4.3). Therefore, we summarize in Section 5.1, the Pepper's design suitability for deployment in high density areas, previous studies of how the users interact with Pepper in semi-crowded environments and the possible forces applied to the surface of the robot by both expected and unexpected contacts. Section 5.2 is dedicated to case studies related to a human-operated motorized wheelchair. It is important to note that the state of the art shows no previous records of studies taking into account the CROWDBOT project constraints.

4.1 Pepper Robot Interaction

Safety is one of the must-have features of the Pepper robot, especially because it is mobile and it is supposed to operate in a human-centered environment and interact with people in close proximity. Compared to the bipedal Nao robot, Pepper is relatively less prone to falling because of its three-wheel locomotion system and very low center of gravity. An Inverted pendulum control further helps to stabilize the robot. Modules like fall manager and push recovery (Balance manager) help to deal with unexpected physical interactions of the robot with both world and people. This modules allow the Pepper robot to balance during its own dynamic motions (through a high level controller) and when external forces are applied. The navigation speed limit of Pepper is 2 km/h and an emergency speed limit for push recovery that performs at 3.6 km/h. Moreover, Pepper is also equipped with a stop button at the back of its neck.

In order to ensure safety, a two-step process is performed during the shutdown of the robot by pressing the chest button: the robot first goes to a relaxed and safe position and then sets its motors off. The robot is designed to minimize any sharp edges on the external part of the body. In case of a hard enough push (so that the robot might fall) prompts the robot to cut all motors to fall softly on the floor. In case of a possible safety issue when falling, the design limits the weight in the upper body.

The *Pepper* robot is complying with some of the recommendations of ISO 13482. Specifically in section 5.10, which highlights the hazards due to robot motion and additional safety requirements. For example, the robot must stop before collision with any obstacles detected (above 1.5cm). The elevation of base from the ground is ~2cm, low enough to avoid rolling over a foot. Moreover, it is equipped with touch reflex, reduced movement speed, blind zone analysis and navigation module to create a local map for safe navigation. In the last case, when moving inside an unknown zone, the limb speed is reduced to avoid damage. Additional design features of the robot also include avoiding mechanical resonance effects that can lead to instability, keeping low masses of moving parts as well as the manipulators, the usage of materials or structures for reducing force impact [1].

4.1.1 Non-Physical Interactions

A field study conducted by Softbank Robotics in an area with a high density of people in 2017 with 150 people provided an estimation of the user and Pepper robot's proactivity in terms of engaging into an interaction. The static robot, driven by its robot's autonomous life behavior showed a proactivity in the engagement of about 40% whereas the other 60% corresponded to an interaction triggered by the people passing by.

In this case, people were gathering around the robot for both interacting and observing the interactors. In fact, such congestion was feeding the interest of the people around the location so a circle tends to be formed in many cases, reducing any chance of physical contact. Despite the fact that physical interactions become more relevant due to the nature of CROWDBOT project, there are two important considerations to be extracted from this study.

Firstly, robots attract the inexperienced people's attention in a great manner, conditioning their behavior, becoming a focus of attention and avoiding the construction of a scattered environment where to navigate. Secondly, it suggests that a more suitable deployment should be carried out in an environment where the novelty effect around the robot is minimized so that it can move freely through a homogeneous crowd. For instance, a large space with recurrent attendees in the context of a conference or similar would be an interesting event to consider a possible experimental scenario in order to reduce such behavior.

Additionally, when the engagement is triggered by the human, there are two common trends to consider for both physical and non-physical interactions: they are 1) the use of voice as a vehicle for claiming attention and/or 2) the hand's waiving or greeting. These cases are extremely relevant in order to set the first impression and expectation for the user in a context of social navigation.

In this regard, the H2020 European project CARESSES[1] has confirmed the usefulness of the tablet, becoming a bridge between the non-physical and physical engagement, in a context with noise or limited access in order to smooth the interactions. In addition, the tablet provides a better welcoming since inexperienced users feels more comfortable with a known device, thus reducing the shyness.

4.1.2 Physical Interactions

In any physical direct or indirect interaction with Pepper, a straight goal is to eliminate any risk of injury from users and passerby's. In order to reduce these cases significantly, precautions are taken during the platform design (see Section 5.1), and the control implementation which takes advantage of the sensing and perception capabilities available. An additional area of interest in crowd navigation focuses on the reaction of the robot while standing and a person does not notice its presence and walks towards the exact same position. It would be natural for a person standing to suddenly move when noticing a chance of collision. Then, if the collision takes place, the human body reacts naturally, trying to minimize the impact.

In this line of thought, analyzing the displacement of the joints when a collision occurs on the robot's surface is profitable in order to understand how an impact can be absorbed more naturally. Therefore, Softbank has conducted a study to better understand Pepper's joints when reacting to external forces as it is shown in figure 21. A preliminary quantitative assessment shows that both hip and knee behave similarly when an impact is detected either on the torso or the legs. As it can be observed, an impact on the head affects directly the displacement of the neck, in a lower manner the hip, and finally, the abortion in the knee becomes minimum. Finally, dependency between joints need further exploration when reacting to unexpected pressures.

The study presented in section 5.1.2 provided an insight into the most common and intentional physical actions from a user towards the robot. As it is presented in figure 21, touching the hands of the robot is the preferred action for the users followed far away from the head contact. However, both cases are a relevant for consideration in order to provide suitable reactions to intentional human physical interactions.

4.1.3 Use Case Scenarios

Possible use case scenarios contemplated after a second updated and extended integrated robot system for experimental scenario is scheduled for submission as part of deliverable D5,3, are inspired in the support for elderly, visually impaired individuals as well as people with reduced mobility. Specifically, the approach would consist of allowing the target individual to use the physical contact with the robot in either shoulders or head in order to walk. Further research needs

[1] http://caressesrobot.org/en/

to be performed and professional counselling acquired in order to ensure viability. However, preliminary studies in the context of ROMEO2 project[2] and professional input encourage such scenario. In this way, Task 3.5 that focuses on shared control navigation, can be further exploited in order to develop strategies for merging user control and planner suggestions.

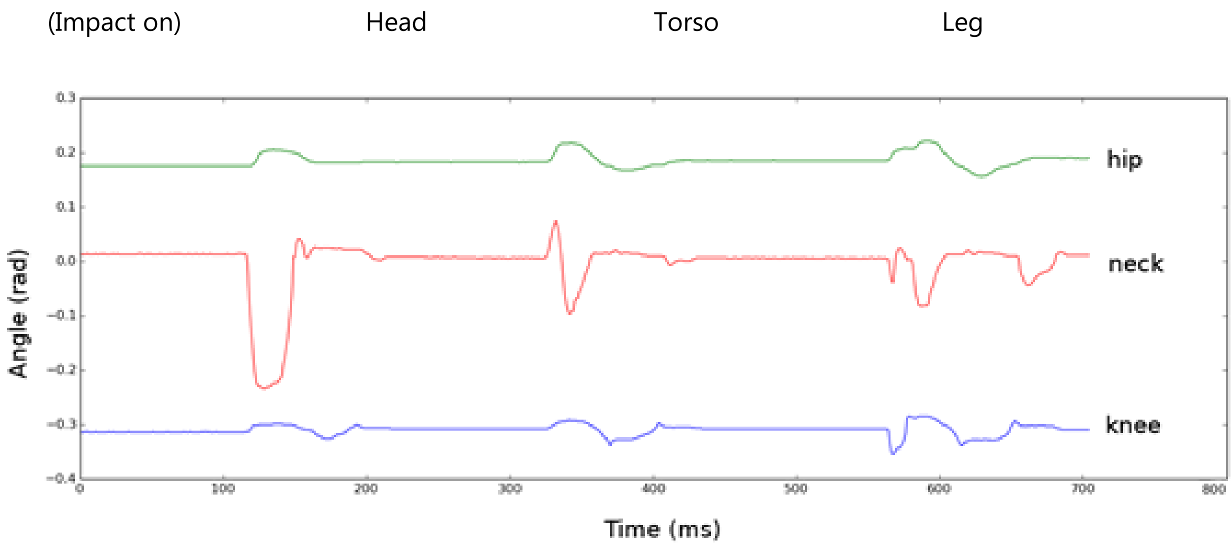


Figure 21: Study of the joints displacement (hip, neck and knee) due to a frontal collision in head, torso and leg sections of Pepper

Autonomous Electric Powered Wheelchair Interaction: Despite the fact that power wheelchairs were introduced during World War 2 and have been widely used by elderly people and handicapped, manual operation by such persons of wheelchairs is still difficult [1]. Studies have revealed that the acceptability of fully autonomous wheelchairs is still challenging and highly dependent on the severity of the disability [2]. In [3] it is shown that 9 to 10 percent of patients who have received non-autonomous power wheelchair training find it extremely difficult to use. The difficulty increases significantly if they are specifically asked to accomplish steering/maneuvering tasks. To address this challenge, assisted control architectures have been introduced during last two decades. Such systems can provide some sort of autonomy from which the users can benefit [3]. However, the acceptability of assisted control systems is challenging and it depends on the level of autonomy and the disability severity [2]. For example, the users are more open to short-term autonomy than a full one; e.g., cross doors, get on and off vehicles [2].

Thus, human factors are crucial and must be considered in design and development of smart wheelchairs [4]. To this end, human factors have been extensively studied in seven categories: Human-robot interaction [5], interface [6], learning [7], operation [8] [14], physiology [9], platform [10] and social issues [11]. One of the early outdoor studies on the use of smart wheelchairs was conducted with a pair of computer-savvy users maneuvering a wheelchair under an assisted control and compare it to the standard manual control in power wheelchairs [14]. Other studies followed suit and we refer the reader to the extensive surveys on power/smart wheelchairs

[2] https://projetromeo.com/

presented in [4] [12] [13]. CROWDBOT studies the use of assisted/smart wheelchairs in specific contexts, namely in dense and crowded environments, that bring challenges not covered in previous studies. Most importantly, CROWDBOT seeks to determine new control mechanisms that will decrease accidents that occur from the use of motorized wheelchairs.

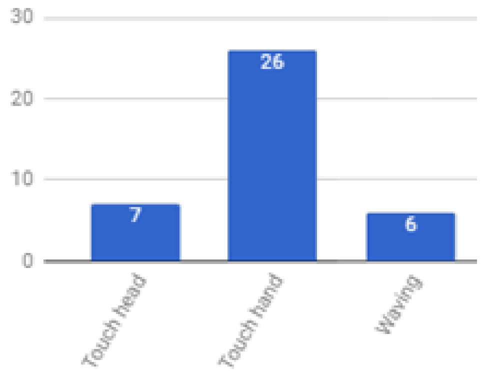


Figure 22: The most common user's physical interactions with Pepper conducted with 150 people.

Most of non-smart, motorized wheelchair accidents are caused: a) by environmental conditions such as inclination of sidewalks, which may cause the wheelchair to crash against a car or the user to fall down [15]; b) by difficulties in maneuvering the wheelchair [16] in complex environments, such as doorway passages, narrow corridors or crowded environments; c) and finally by cognitive fatigue due to increased workload while operating the wheelchair, which may distract the user's attention and be the cause of serious accidents [16].

The CROWDBOT project will assess whether the use of an intelligent driving assistance system for robotic wheelchair will reduce these causes of accidents. Furthermore, it will determine specific cases where the wheelchair must navigate in densely populated environments and crowded traffic situations (with different density, flow, pattern and activity). The specific scenarios and metrics for assessing the performance of the intelligent controllers will be agreed with the main stakeholders and the Ethical Advisory and Safety Board (ESAB).

References

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