Dutch Robotics Roadmap

Strategic Agenda RoboNED part 2

Edited by: Ir. D.J.B.A. Kranenburg - de Lange
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1 Introduction

2 Navigation and Motion Planning

2.1 Introduction

Mobile robots need to move in 2D and 3D through known and unknown, static and dynamic, structured and unstructured environments, indoor or outdoor, intra-corporeal or extra-corporeal. Besides, they have to be able to deal with unfavorable conditions for sensing, mobility and manipulation, like varying light conditions, water, dust, mud, slippery surfaces etc. This relies on the robots' observation of the world through its sensors and data acquisition through other robots and systems, such as surveillance cameras. They need to localize themselves (SLAM) and move to target destinations (Motion), while avoiding obstacles in a safe and efficient way.

Simultaneous localization and mapping (**SLAM**) is a technique used by robots and autonomous vehicles to build a map within an unknown environment (without *a priori* knowledge), or to update a map within a known environment (with *a priori* knowledge from a given map), while at the same time keeping track of their current location in this map.

Motion for a robot can be defined as a path in the configuration space (the map). The motion planning problem asks for determining such a path through the free space (i.e. without collisions) in an efficient way or according a required pattern (e.g. coverage).

The basics of the navigation problem have been solved by means of data Triangulation or Time of Flight methods, based on a variety of sensors like IR, US, cameras, Laser Range Scanners (LRS) and Time Of Flight (TOF) cameras. However the complexity of our environment is such that with the actual available algorithms and software only the simple situations can be addressed. Autonomous robots get stuck in complex situations, lose their way and arrive at the wrong location with all possible consequences. Corrective measures are complex and expensive because they often require the infrastructure of the environment to be adapted to the robot.

2.2 Analysis

2.2.1 Needs

Robust Slam. Mobility needs precise maps and correct localization in complex dynamic environments, without the need for manual correction nor for external adaptations to the infrastructure, like adding beacons or other guidance systems.

Effective motion planning. Mobile autonomous robots need to move from one location in a map to another. A lot of scientific work has been done to create algorithms for motion planning, however in the complex reality they fall short. At this moment, both commercial and scientific projects require ad-hoc algorithm development which is time consuming and in-efficient. Better universal applicable motion algorithms would facilitate the development of useful functional robots.

Cost reduction of navigation hardware and software. Realizing robust Navigation requires expensive sensors like laser range scanners or TOF camera's. The cost level of this hardware prohibits the realization of acceptable business cases for commercial or consumer robots on a larger scale. (See also chapter 3: sensing & perception).

There is no generic navigation software that can be re-used for different applications in an industrial (i.e. non-scientific or -experimental) approach. As a consequence, software needs to be developed specifically for each robot application, leading to a cost level that prohibits viable business cases.

Robust quality software. Available open source software libraries differ in quality and have all kinds of different licensing requirements.

Speed. A mobile robot needs to react fast when moving through a dynamic environment in which people and objects can appear suddenly. Complex and dynamic environments provide an enormous amount of data that need to be processed very fast.

Safety. A mobile robot needs to move through a complex and dynamic space without damaging any person or object. Particularly important when moving in high traffic areas that are accessible by anyone or when working with heavy weight robotic machines like in industry or agriculture. Today's solutions are based on expensive LRS sensors. Economical and ready-to-use anti-collision modules need to address liability issues sufficiently.

Robustness for external influences. Robots must be able to navigate day and night, sunshine or rain/snow, clean or dirty.

2.2.2 Offers

Low cost sensor fusion. In order to reduce hardware cost, a combination of low cost sensors for short range and long range can be combined with a smart algorithm to translate all data into a precise map.

Generic software architecture: re-usable with the possibility of plug-ins. Quality software architecture that can be adapted to specific applications by means of plug-ins will reduce the resources for software development enormously.

3D cognition. The performance of a mobile system crucially depends on the accuracy, duration and reliability of its perceptions and the involved interpretation process. Laser Range scanners and 3D cameras enable robots to scan an environment in three dimensions. Many challenges remain in the interpretation of the data in order to realize robust navigation. These challenges are even bigger when using a combination of different types of sensors (sensor fusion). It is not only about detecting obstacles but also about giving a meaning to them. This feature and object recognition enables the robot to execute a task: e.g. recognizing crop to be harvested, areas to be cleaned, appliances to be operated.

Behavior-based learning. A control system for an autonomous robot has to cope with uncertainty in sensory readings and actuator execution as well as handle dynamic changes in the environment. The traditional robot software architecture uses deliberative reasoning in the form of sensing, planning and action. It is difficult to accommodate sensory uncertainty and the environmental dynamics in such an architecture. Reactive or behavior-based architectures are better able to handle the problems inherent in the deliberative architecture. The basic component in such an architecture is a group of behaviors. Behaviors directly convert sensory information into motor actions without complex reasoning. The conversion enables robots to respond to environmental changes promptly.

2.2.3 Matches and Gaps

The general navigation requirements Robustness, Speed and Safety can be addressed by developing re-usable generic quality navigation software architecture with plug-ins for specific application requirements. This navigation software deals both with Slam and with Motion Planning.

The generic software will reduce time to market and R&D cost for robot developments. In combination with low cost sensor fusion this will enable more viable business cases and drive the development of the robotics sector.

2.3 Focus and Planning

2.3.1 Subject 1: Overview of available sensors and software

- Description: The creation of a structured and accessible overview of all possible sensors and available software/architecture for navigation with an assessment of performance
- Problem: as Robotics is a new and dynamic activity, many new researchers and developers spend a lot of time to get an overview of up to date technology and performance,
- Solution: centralize information
- Background: Literature / existing approaches
- Key players in the field: RoboNED (Robodb.org), Universities

2.3.2 Subject 2: Low-cost sensor fusion

- Description: The development of a robust generic SLAM system based on a combination of low-cost sensors like Infrared, Ultra-Sonic, gyroscope, wheel encoders, structured light cameras (e.g. Kinect), RGB cameras, short range laser range scanners.
- Problem: Actual SLAM is based on long range Laser Range Scanners that are too expensive to be competitive in comparison to manual labor.
- Solution: The creation of a robust functional SLAM platform based on a sensor set with a max cost of 300€.
- Background: many institutions and companies are experimenting with e.g. Kinect sensors, yet all on a too small scale to create a general applicable solution. Joining forces will be beneficial to all stakeholders.
- Key players: e.g. RoboNed, Universities, Frog, Philips, Schuitemaker, Lely.

2.3.3 Subject 3: Generic motion architecture

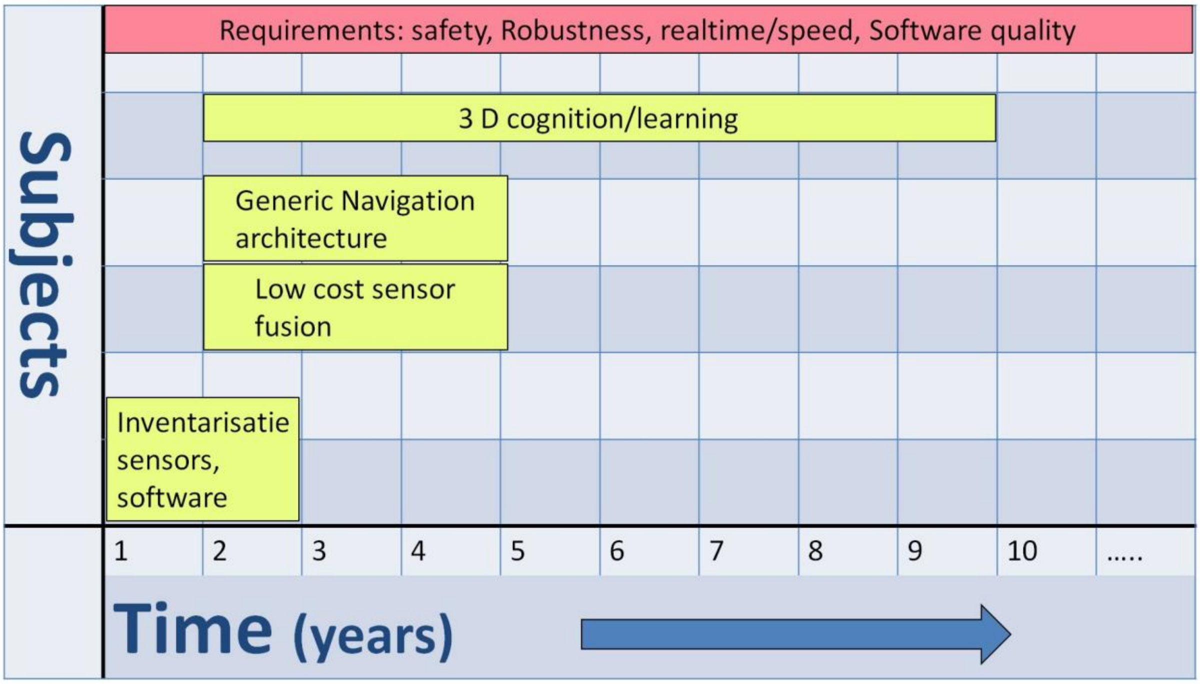
- Description: the creation of a generic software architecture to integrate SLAM with Motion Planning of which the software quality is controlled.
- Problem: There are many open source software architectures and libraries available. However, in general the quality is not controlled of these architectures and libraries. Without quality assurances one cannot use these architectures and libraries to build an actual application. Therefore every company has to develop these building blocks from scratch leading to high development cost and unviable business cases.
- Solution: Create with a Dutch consortium a high quality software architecture and libraries for different robot applications. The quality should be controlled.

- Background: Sharing the development of such architecture will help Dutch companies to develop robot applications with a viable business case.
- Key players: e.g. RoboNed, Universities, Frog, Philips, Schuitemaker, Lely.

2.3.4 Subject 4: 3D cognition & behavioral learning

- Problem: Most mobile robots operate in unknown, uncontrolled environments. Taking all the use cases into account that can occur is undoable. Explicitly designing for all these use cases will lead to large decision trees that are not maintainable.
- Solution: Mobile robots should be able to handle cases which they are not explicitly designed for. This can be achieved by higher levels of 3D cognition and behavioral learning. A robot should be able to learn from its own mistakes. But it could also be very effective if a robot could learn from other robots or from humans.
- Key players: RoboNed, universities

2.3.4 Planning



2.4 Conclusions and Recommendations

Creating and keeping an up to date overview of available sensors and software for navigation particularly facilitates a quick familiarization and acceleration for new researchers and developers in the area of Robotics.

Working on a generic navigation architecture and low cost sensor fusion needs the facilitation and coordination of a platform of participants that stimulates collaboration and addresses competitive interests and intellectual property.

The area of 3D cognition and behavioral learning offers interesting academic research possibilities with broad application options.

2.5 Contributors

The following individuals have contributed to this chapter (in alphabetical order):

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3 Sensing and Perception

3.1 Introduction

Sensors are very important for robots to react on their environment. They rely on vision, touch, sound, conductivity, and many other sensing techniques. Often, these sensors lack in robustness, functionality and performance, and are very expensive. Combining the needs of multiple application domains can enable the required innovation to improve the state-of-the-art in sensing. Moreover, the intelligent interpretation of sensor data, perception and sensor fusion of different sensing principles is very important to achieve the goals.

3.2 Analysis

Sensing and Perception are critical for robots in the care, cure, agro- and food and manufacturing domains. Robust knowledge of understanding what is in the work area, where it is, are required for robots in these areas to deal with unstructured and varying environments. The computing power needed for robots to support the type of processing and decision making to become adaptive to the environment is now affordable and powerful enough. New generations of sensors are becoming available that are mature enough to build 3D information about the robots surroundings required for the perception of dynamic and unstructured environments. The technologies developed in the different domains may be transferred and adapted to other application domains.

In this section first the needs in sensing and perception will be identified which are applicable in all the different application fields. In the next step, we will go over the technology offers and availabilities. Then the needs and the offers will lead to potential matches and gaps.

3.2.1 Needs

Better and cost effective 3D sensors and algorithms are needed to yield comprehensive, pervasive, redundant and accurate 3D data. Furthermore, the sensors need to be robust against varying lighting conditions and have adequate spatial resolutions. There is an increasing need to integrate haptic sensors in robotics as robots are entering more and more the "human" domain and will not be fixed to the infrastructure but autonomous and interact in the human environment. Combining sensors and fusing information from other modalities e.g. other spectral information, may improve or help the view of robots on the surrounding world.

Robust perception is the key technology for the next generation robotics for a variety of applications. These application areas require operation and sensing in unstructured and cluttered environments. Moreover in many applications the robots have to step up from only having to deal with static scenes to be able managing dynamic and more complex scenes. Application uses range from advanced crop management tasks in green houses to in-home assistance for the elderly and disabled. In these environments it is an essential task for the robot to identify objects robustly and reliably and have their position accurately determined, so that they can be manipulated in some way.

For the next generation robotics a better understanding of the surrounding 3D world is a necessity. Robots should be able to be robust against slightly changing appearance of objects within the same category.

3.2.2 Offers

The situation in the Netherlands is that for conventional cameras and sensors we don't make the imaging chips and cameras. At European level there are excellent camera manufacturers which can be bought through an extensive network of dealers in the Netherlands. True 3D Sensors like TOF (time-of-flight) cameras, laser scanners are also manufactured outside the Netherlands. TOF sensors are becoming interesting sensors for 3D applications as the spatial resolution is improving and at more attractive price levels. The Swiss based company Mesa Imaging and the Belgian spin-off Optrima of the Brussels University are driving forces behind 3D TOF development. Other 3D imaging sensors are stereo cameras which are available by international companies such as Point Grey Research, Inc (with the Bumblebee product line) and Videre Design LLC (with the Apparan family for high-volume applications).

Recently we have witnessed the arrival of the Kinect 3D sensor, which originates from the gaming industry. As this sensor is mass produced and used as control for a gaming console it is a cheap 3D imaging device. The depth sensor consists of an infrared laser projector, which projects a dot pattern, combined with a monochrome CMOS sensor, which captures video data in 3D under any ambient light conditions. The Kinect sensor has gained popularity in many university robotic research projects.

In the Netherlands sensor development takes place primarily for niche markets. There are technological spin-offs from universities that develop new sensor type of cameras. For example TeraOptronics is a small company that originates from the Radboud University of Nijmegen (RUN). They will develop a new type of terahertz camera, the TeraCam, which looks at the far infrared spectrum. Quest Innovations is a company that develops and manufactures high quality multi-spectral cameras and dedicated software for advanced imaging applications. In the Netherlands there are companies active on other sensing modalities such as research and development of force feedback/haptic sensing, such as Moog (Haptic Master).

There is a lot of research ongoing in sensing and perception issues in the various application domains. The technical universities have strong research programs in robotics with emphasis on modeling and self-learning. The Wageningen UR has an expertise centre on vision and robotics aimed at agro- and food industry. Research institute TNO is active in the field of health care. Apart from universities and research institutes, Philips research is a big player active in the domain of domestic services and health care.

3.2.3 Matches and Gaps

Sensor development is driven primarily outside robotics. The strategy here is to ride the wave. When better sensors come along, replace the obsolete sensors by the improved ones. This might be on the aspect of resolution, completeness of the (3D) data or more robust against varying lighting conditions. As aforementioned, in the Netherlands there is no real camera industry, special sensor research and development may take place for niche markets. When special sensor development is required for a particular application domain a possible path is to team up with a technological spin-off of a university.

It is important to realize that currently there exists a gap in the sensor technology needed for 3D imaging and what is currently available on the market. However, some developments outside robotics will push sensor development further and comes available such as the Kinect. Others, when there is no driving cross mass market, have to be developed.

In the Netherlands there are many research groups active in sensing and perception in robotics research projects. However, currently, there is a gap between academic research and salable products in the different application domains. For one part the reason is that applications require operation in unstructured and cluttered environments which is not feasible yet. For the other part, it is very difficult to have cost effective solutions.

3.3 Focus and Planning

3.3.1 Subject 1: Localisation and 3D accurate reconstruction

- Description of the context: With robots acting in the human environment there is the need for precise localization and accurate reconstruction of the 3D surrounding. To be of any use robots operating in the human context must be able to identify objects reliably and determine their position accurately.
- Problem statement: Sensing is used by robots to perceive information about the surrounding environment. Combining information from multiple sensors (fusion) or by different standpoints (SLAM) is an important research area. Robots will in future rely on sensory information and have to go beyond the basic modeled settings. Therefore, to provide robustness there is need to have redundant multiple sensors and fusion of sensory information.
- Possible directions for solutions: Making use of open source robotics technology.
- Background, Literature / existing approaches: Open Source Robotics initiatives are i.e. the European OROCOS (Open RObot COntrol Software) project, OpenJAUS, ROS (Robot Operating System) open-source software running on the Willow Garage robots. Of particular interest linked to ROS is the Pointcloud Computing Library (PCL).
- Key players in the field: Universities, Philips Innovation Services, TNO Industry

3.3.2 Subject 2: Better and affordable sensors for 3D and haptics

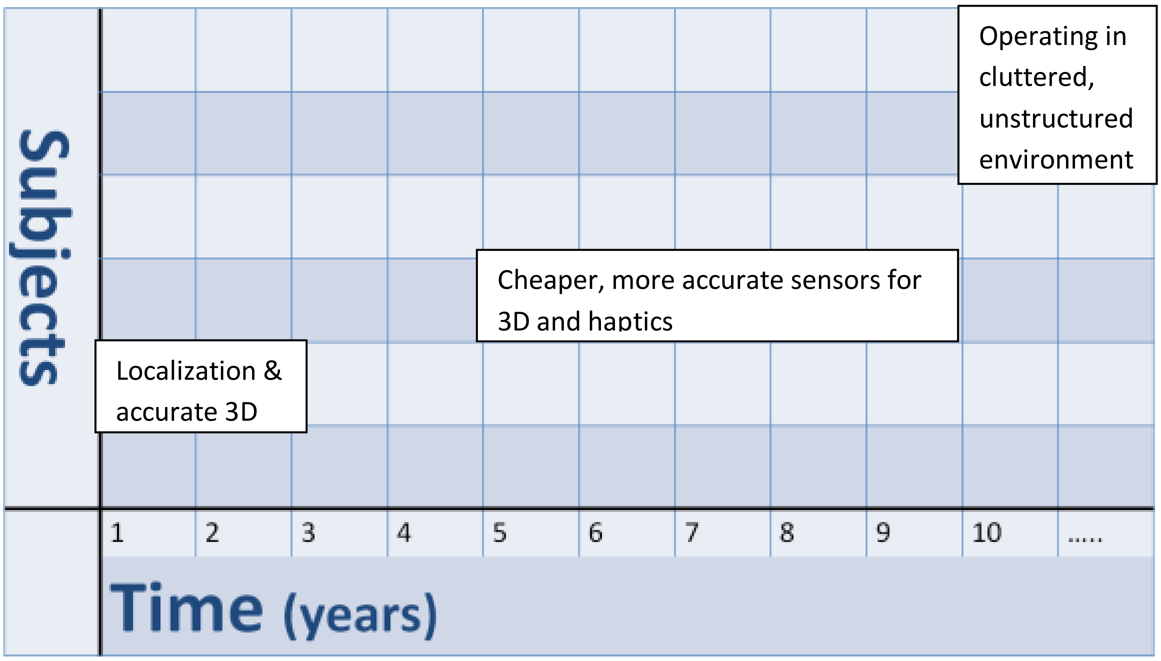
- Description of the context: In future applications domains, robots act in unstructured and cluttered environments. The robot has to build up adequate representations of the surrounding 3D world and be able to cope in real-time with variations in its environment.
- Problem statement: In order to allow for robots to keep track of a dynamically changing workplace advances in sensing and perception technology are required and better 3D sensors are needed. Better in the sense of giving more complete 3D data, at higher resolutions and more robust against external varying conditions.
- Possible directions for solutions: Robotics is not a driving force in sensor development. The strategy is to ride the wave and put new sensors into practice when available. Special sensors like TOF for 3D imaging are being developed in other European countries like Belgium and Switzerland. In the Netherlands there are companies who focus on technology development of sensors in niche markets.
- Background: Literature/existing approaches
- Key players in the field: Optrima, Mesa Imaging, mainstream camera manufacturers, MOOG.

3.3.3 Subject 3: Better understanding of 3D world

- Description of the context: We will see a growing dependence on robotics in the future, as part of the working force to carry out tasks in unstructured environments, e.g. in the agriculture domain doing crop maintenance tasks in greenhouses. But also in the care domain to help the elderly and disabled. For this robots need to operate in changing environments and being able to cope with unstructured and cluttered working environments. These robots cannot rely any more on fixed preprogrammed models but must be able to adapt and learn.
- Problem statement: The challenge is to combine sensory information with higher level perception and to go beyond a priori modeled information.
- Possible directions for solutions:
- Background: Literature/existing approaches
- Key players in the field: Universities

3.3.4 Planning

- Short term Goal: Localisation and accurate 3D world reconstruction methods (2013)
- Mid term Goal: Availability of cheaper and more accurate sensors for 3D imaging and haptics (2017)
- Long term Goal: Better understanding of 3D world, robots operating in cluttered and unstructured environments, self-learning capabilities (2022)



3.4 Conclusions and Recommendations

Sensing and perception are key factors in robotics, without it robots are confined to static structures, and blindly execute fixed pre-programmed behavior. When robots enter the "human" domain to assist the elderly or the disabled, or when robots will join the work force far better sensing and perception technology is needed than available right now. When entering the human domain robots have to cope with unstructured environments which may be cluttered with all kind of known objects and objects not seen before. This will pose a challenge to robotics research the coming years to develop technology able to operate, safely, quickly and accurately in this environment.

This is a common challenge in the application domains of cure, care, domestic and agro and food. In the Netherlands there are many strong research groups active in innovative robotics projects. It is recommended to focus research effort and knowledge development on operations in complex, unstructured and changing environments.

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4 Interactive Systems

4.1 Introduction

Interaction between users and robots is getting increasingly important. Robots are getting more interwoven in our daily lives, more divers in application (outside factory walls), and need to be controlled by non-trained non-professional users. One natural way for a human to control a robot is by physical interaction, i.e. feeling counteracting force on the master that the user is using to control a robot. Other aspects important in human-robot interaction are (cognitive, multi modal) interfacing, graphics and supervision.

4.2 Analysis

4.2.1 Needs

The general needs that were prominently present in the working group:

- ***Intuitive interfaces for elderly***
  The challenge here is to design robot interfaces that require hardly any specific user-knowledge and fit to our everyday tasks and interaction in life. This will be of particular interest for a large group of potential beneficials; the elderly.
- ***Robot safety and robustness***
  The challenge here is to design intrinsic safe and reliable systems and subsystems, both on component and on task level. This will enable robots to enter our daily lives and living environments without any introduction of potential dangers. Also robustness of operation is a prerequisite for usefulness.
- ***User acceptance***
  The challenge here is to design robots in such way that it is accepted not just as a side goodie, but as a worthy and usable supportive device (like cell phones). Therefore it needs not only the above-mentioned points, but also aesthetics and other ‘soft-factors’.
- ***Social accepted behaviour***
  The challenge here is to design robot responses that fit our expectations with respect to the way we social interact as humans, e.g. a crude robot will not be accepted.
- ***Automated shared control***
  The challenge here is to design interfaces that need little details from the human controller on the one hand, but do not act autonomously against the will of the operator on the other hand. Especially for impaired people who potentially have a great benefit from robotic support in adl-tasks, the means to control quickly and accurately are limited.

Besides these general needs, there were also some more specific needs:

- a list of usefull (robot) tasks and definitions (what can we do, and what not)
- roadmap of human-robot labor in care (from the demand side)
- standards for robot platforms (interfaces, OS, simulation tools, etc..)

4.2.2 Offers

The workgroup offered players from both industrial and from more service oriented robot suppliers, from both industry and from academia and knowledge institutions, from both SME and from large industry, and from various application fields (domestic, care, production, agricultural,…). Altogether, the offers were very different and broad, which typically illustrates the vast and diverse field of robotics.

4.2.3 Matches and Gaps

Typical for the workgroup outcome was the vast list of needs compared to the list of offers. Since the gap between needs and supply was still large, the suggestion was made to launch pilots that would serve as a 'connecting vehicle'. The two pilots that were defined are given in the next section.

4.3 Focus and Planning

For the focus and planning the two pilot projects which came from the workshop are used.

4.3.1 Subject 1: Home intelligence and automation

- ***Description of the context***
  Keywords are: Domotics, elderly, care and supported living.
- ***Problem statement***
  One of the major problems is that there are no standards yet (both from the ICT and from the human perspective). This makes it very difficult to follow a distributed development development strategy, e.g. making apps that work in various environments and on various platforms. The consequence is that the successes that are achieved only work for a specified situation and environment, with no useful building blocks being recycled in the next project.
- ***Possible directions for solutions***
  We propose to develop a platform with several key stakeholders (e.g. within the FET Flagship RoboCom, or Future ICT), and build on that platform in a systematical way. Robotic entities that that could be coupled to this platform are: vacuum robots, eating robots, lifting support, transfer, (granny-)butler etc… By building the functions of these robotic entities on a well defined platform the interfaces with the living environment will be more uniform and the speed of development will increase, bringing new business cases.
- ***Background: Literature / existing approaches***
  Some European projects are already ongoing within FP7, such as: KSera, Mobiserv and SM4all
- ***Key players in the field***
  De ICT platforms Smartliving en Domotics already joined forces with RoboNed in the seminar of September 30 2011. The input and the members from this workshop can serve to form a strong fundament for this project.
  From industry: Philips Consumer Lifestyle (NL), Toyota (JP), Electrolux (SE), Roomba (USA), NEC (JP), …

4.3.2 Subject 2: Soft robotics

- ***Description of the context***
  Keywords are: Soft and safe robots, cognitive and physical interaction
- ***Problem statement***

The major problem in interaction between human and robot, is the intuitive and safe interaction. This requires both new control paradigms, and new (soft or compliant) actuators and proper cognitive interaction to interpret human tasks.

- ***Possible directions for solutions***
  There are quite some directions, which offer solutions. However, these are mainly from an academic nature.
- ***Background: Literature / existing approaches***
  Some European projects are already ongoing within FP7, such as: Saphari
- ***Key players in the field***
  Academia: 3TU (NL), MIT (USA), Stanford (USA),…
  Industry: Festo (DE), DLR (DE), …

4.4 Conclusions and Recommendations

The workshop human robot interaction and haptics showed that there is a need for robots with intuitive interfaces, that are robust and safe, which are socially accepted, and show social accepted behavior, and can perform automated shared control with humans. However, few offers in this direction were found. Two pilots were suggested to bridge the gap between needs and offers: home intelligence and automation and soft robotics.

4.5 Contributors

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5 Learning and Adaptive Systems

5.1 Introduction

Future robots must be able to effectively learn from experience, and actively acquire knowledge about their environment, so that they can optimize their performance and realize an appropriate degree of autonomy. Only in this way, robotics will penetrate into new domains, beyond standard factory automation.

5.2 Analysis

Adaptation and learning are the key technology for autonomous operating robots. In this section we analyze what situations can benefit from learning and adaptation, which techniques are available and which challenges are still to be solved. From this analysis we can then find matches of applications and the available techniques and tools.

5.2.1 Needs

Adaptation and learning features are desired in the following situations:

- Learning can be used as a means to deal with uncertainty, possibly in an optimal way. A properly designed learning system will seek to optimize its behavior over a variety of real-world conditions, which would otherwise be difficult to model for the purpose of off-line design.

- A robot is required to deliver steady performance under largely varying conditions. A typical application example is the agricultural sector, where crops will vary in size, shape, color and rigidity. Similarly for domestic applications.

- A cognitive, autonomous robot serving humans or working together with humans needs to learn from this interaction in order to anticipate the needs of the human and respond in an appropriate way.

- Learning can save design and development time. Versatile robots can be equipped with standard learning algorithms (so requiring low design effort) and tuning for a specific task is achieved through learning. Learning can also deliver solutions to problems that we are currently not able to solve through off-line design, for instance, due to the lack of suitable methods and tools.

- An adaptive or learning algorithm can compensate for imperfection of components, such as joints, actuators, etc. High-performance system can be realized with low-cost components, and, in this way, compensate for ageing, wear and tear.

- Learning algorithms can help recover from large faults. If a part of a robot is damaged, learning can be use to construct new motion primitives that are compatible with the new, unexpected robot morphology. Analogously, learning allows for the use of physical tools for which the robot was not programmed, e.g., a heavy hammer.

In the above situations, learning and adaptation can be used in two essentially different manners:

1 Learning solely before the deployment of the robot (cf robots go to school first), while the acquired skills are frozen afterwards in order to have a fully predictable system with guaranteed performance (cf robot passed and exam and is ready for the real work). Learning before deployment can take place under specifically designed conditions that are safe for the robot and its environment, that do not lead to economical losses, and where the learning process can be optimized. Think of, for instance, task shaping: the learning process starts with simplified version of the eventual task (which is easier to learn) and then the complexity gradually increases, until the original task is solved. Various forms of learning can be applied, such as learning by demonstration, imitation learning, etc. Robots operating in a distributed system can learn by observing (or even simply copying) each others skills.

2 On-line learning throughout the lifetime of the robot. This situation is clearly more challenging, as the behavior of the learning robot may possibly become unpredictable and the learning algorithm typically has to deal with corrupted data (outliers) and unexpected disturbances. Furthermore, the optimal learned behavior of the robot should be alternated with exploration to acquire new knowledge. If the challenges of this setting are properly addressed, we get a very powerful concept. Learning can then be regarded not only as the improvement of the robot throughout its lifetime, but also as the evolutionary process over generations of robots. Knowledge and skills acquired in one robot generation are passed as initial solutions to the next generation. By monitoring this evolution process, robot designers can learn new solutions as well!

Regardless of the specific mode of learning, the basic requirement is that the learning process should be reasonably fast (i.e., there must be some clearly observable improvement in time), computationally efficient, the convergence to acceptable behavior must be guaranteed and preferably nearly monotonous (robots do not learn and subsequently unlearn). To facilitate effective learning, methods are needed that can automatically identify important features on the sensing side and motion primitives on the actuation side. These primitives should be parameterized by a small number of parameters, so that they can be inherited from situation to situation. A suitable combination (or interpolation) of the primitives then leads to the required, possibly complex, behaviors.

Another challenge is to find the right balance between the amount of prior knowledge used and the extent of learning from data. The use of much prior knowledge typically means large design effort and cost. Relying too much on data requires rich data sets, i.e., a lot of exploration, and therefore long learning times and poor initial performance.

5.2.2 Offers

Several specific learning paradigms have been developed to such a degree that algorithms are ready for the use (and some already have been used) in real-world applications. Notable examples include iterative learning control (ILC) or simultaneous localization and mapping (SLAM). However, other forms of learning, such as reinforcement learning (RL), have been successfully demonstrated in labs, under well-defined experimental conditions, but no commercial applications have been reported to date. However, the progress in this field is quite rapid and there is a significant coordinated effort worldwide. For instance, the path-integral methods have been recently successfully applied to learning on Willow Garage robots (Radboud University, Univ. Southern California). Novel intelligent sensors (such as Kinect) are important enabling technologies, as they make it possible for the robot to collect information about its environment at a relatively low cost.

5.2.3 Matches and Gaps

While a tremendous number of learning and adaptive algorithms have been developed in the academia, real-world applications are still scarce. It is probably quite safe to state that the scientific community is not yet completely ready to deliver robust learning solutions for practical use. In addition, the tools are being offered by different communities (machine learning, pattern recognition, artificial intelligence, control theory, operations research, cognitive sciences) almost independently, with too little interaction and cross-fertilization between these fields. The final breakthrough into real-world applications can be facilitated by profound integration of these domains.

From the industrial point of view, transparency of the learning process is required, so that one can validate the system. This implies that the solutions learnt must be interpretable to the system designers and engineers. The behavior of the robots should be predictable and the system should know its own limits and should not attempt operate beyond them.

From a commercial point of view it is a challenge to show that self-learning robots are better and cheaper than fully programmed robots. This challenge not only concerns high-tech expensive robots, but especially the cheaper and simpler ones.

5.3 Focus and Planning

Learning and adapting robots are most valuable in changing and unstructured environments. The level of structure varies per industry and will typically decrease along the following line: aviation, agriculture, traffic, medical cure, care and domestic applications. The less structured the environment is, the larger the complexity of the challenges. For more structured environments, we expect a shorter time-horizon for actual applications of adaptive and learning robots. In more unstructured environments, Bayesian and stochastic optimal control methods that explicitly model the uncertainty are required. This significantly increases the complexity and the computational demands.

5.3.1 Subject 1: Robots for agricultural and horticultural applications

- Problem statement: Mechanization and automation of agriculture and horticulture have dramatically reduced workload and increased production. This has been an important driver for economic and social development. However, further automation is hampered by the inherent variability of biological products. Adaptive and learning robots might cope with this problem and lead to a further reduction of labor and increase in productivity. An example of an application in the area is the harvesting of peppers, which have different shapes, sizes and location on the plant.
- Challenge: The application area calls for robust learning solutions, because of the rough environment and the goal to reduce the work load. As there is little room for errors, because of possible plant damage and large financial losses, learning must be applied with caution, starting with the off-line (before robot deployment) mode.

- Possible directions for solutions: The typical operations are repetitive (hundreds of handlings per hour), which enables the use of many learning and adaptive techniques. Most benefit can be obtained at the perception side (fusing visual information with other sensors) and manipulation (careful handling of plants and fruits).
- Background: Lely has shown that robotics is accepted in dairy farming, e.g., milking, stable cleaning and foraging.
- Key players in the field: Priva, Lely, Control, AI and Machine Learning Groups at Universities

5.3.2 Subject 2: Care

- Problem statement: The overall age of the human population increases worldwide, and this effect is stronger in highly developed countries like the Netherlands. Assisting the increasing number of elderly people who need help to perform everyday tasks will soon put tremendous pressure on society. One solution to this challenge can be provided by *robotic assistants*. Besides the elderly, assistive robotics can also help disabled people.
- Challenge: Robots need to learn communicate and interact with people in an appropriate manner and learn to distinguish between normal and abnormal behavior of the subject, without having undesired impact on privacy. The data available to the learning algorithm will be less abundant than in agricultural and industrial applications. Ethical, social and legal norms represent constraints that will have to be properly integrated into the learning techniques. Learning will typically take place online.
- Possible directions for solutions: observation and monitoring of human behavior, assistance to elderly, ill or disabled.
- Key players in the field: Academic hospitals, Demcon, AI and Machine Learning Groups at Universities, Ethics and Technology Groups at Universities

5.3.3 Subject 3: Robots for household tasks such as cleaning or laundry folding

- Problem statement: Nearly everyone would like to have a robot to easy household: this field is a huge potential market! Cheap sensors and actuators are important enablers.
- Challenge: Use standard learning solutions to reduce pre-programming effort. Sensor and motion primitives. Robots must be inherently safe in use (light, soft, compliant).
- Key players in the field: RoboCUP@HOME, RoboEarth, Willow Garage, AI and Machine Learning Groups at Universities, Ethics and Technology Groups.

5.3.4 Subject 4: Autonomous, distributed robotics

- Problem statement: Applications like observation and monitoring for security, environment protection, transport, etc., call for the use of multiple interacting robots. Collective learning of these robots improves the performance and saves time. Techniques developed in this area will have a great impact on other fields of major societal importance, such as optimal control of road traffic networks. In the European Union 44% of goods and 85% of persons are transported by road, and traffic congestion impacts the GDP by a full percent (tens of billions of Euros).
- Challenge: The use of many communicating and collaborating robots calls for the abstraction of sensing and motion primitives and the interchange of primitives between robots and robot generations. Coordination is also a major challenge.

5.3.5 Planning

Short term goals (1 year horizon):

- Take steps to join academic comunities (machine learning, pattern recognition, artificial intelligence, control theory, operations research, cognitive sciences), societal and industrial partners.
- Inventarise existing possibilities and carefully define suitable pilot projects. Analyze what is missing in our current knowledge and tools in order to enable real-world applications of learning and adaptive robots (in terms of algorithms, sofwtare and hardware).
- Define and secure funding of projects.

Mid-term goals (5 year horizon)

- Robust learning solutions, acceptable for robot applications for real-world tasks.
- First autonomous self-learning robots in industrial and agricultural environments.
- Demonstration of learning solutions for domestic, cure and care applications. Awareness of public, acceptance of learning robotic systems (we need to bring robots to the public in a safe and easy to accept manner – e.g., through musea, exhibits, etc.).
- Visible joint research activity, lessons learnt from the first applications help form research directions.

Long-term goals

- Ability to learn abstract information and interchange between robots.
- Self-learning robots for domestic use.
- Expertise on learning solutions from various disciplines and their applicability, strengths and weaknesses. Standard, integrated and reusable tools and solutions, software and hardware standards.
- Solid academic expertise and reputation.

5.4 Conclusions and Recommendations

Adaptation and learning capabilities are crucial for new applications, in which robots have to deal with varying conditions and unexpected situations. Most pronounced examples are agriculture, care and domestic applications, but many other applications can benefit from learning solutions, such autonomous distributed robotic systems for monitoring of the environment, traffic, etc.

Learning and adaptive techniques have been successfully demonstrated under controlled conditions in labs, but robust solutions for practical use are not yet ready. In order to take major steps forward, we need a cordinated approach of various, up to now quite disjoint, academic comunities (machine learning, pattern recognition, artificial intelligence, control theory, operations research, cognitive sciences) and industrial partners.

5.5 Contributors

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6 Software Engineering for Robotics and Automation

6.1 Introduction

This Chapter focuses on those aspects of software engineering for which:
- robotics will be the driving application domain, because more traditional drivers such as embedded systems, automotive or aerospace are not confronted with the same system-level complexity challenges as robotics;
- there is already an existing and competitive basis within RoboNed; and
- industrial exploitation can realistically be expected within the Netherlands.

The latter holds for, both, the exploitation of the roadmap outcome via technology providing companies that add the roadmap outcome to their already existing portfolio of products and services, and the application of the roadmap outcome in the agro & food, horticulture, and health sectors.

6.2 Focus and Planning

In the above-mentioned context, the Chapter identifies two key focus lines for academic research in the next decade:
- the methodology of complex systems engineering, and
- task-centred robot programming.

The former has already a solid foundation in the Dutch academic research in "model-driven engineering" for mechatronics (in this domain, the Dutch universities play a leading role in Europe), but must be "scaled up" to the higher complexity challenges posed by robotics. The latter research line can be expected to be driven ("science & technology pull") by the above-mentioned applications domains; many experts in those domains are already available in the RoboNed consortium, and are motivated to:
- provide the domain expertise and task semantics which are indispensable inputs to the research (and give it a high competitive advantage!), and
- engage in intensive cooperation with the academic researchers to help them realise the envisaged scientific and technological innovation.

The roadmaps for both focus lines are explained in more detail below.

6.2.1 Subject 1: Methodology of complex systems engineering

The complexity encountered in future robotics systems comes from the various and diverse interactions between lots and lots of functional components that are required to let the robotic systems solve their tasks. There are two major differentiators with respect to other domains with complex engineering challenges, such as automotive, aerospace, mechatronics, and embedded systems:
- the robot will be just one of many "agents" in an environment with many "peer robots" as well as humans. Hence, "machine performance" will become of secondary importance compared to robustness and, especially, safety and human acceptance.
- the robot will be expected to (re)act autonomously, over extended periods of operation, and to learn and adapt to its environment and the "peers" it interacts with.

Nevertheless, the software engineering requirements and expectations remain basically the same as for "easier" domains, in that developers in robotics will request software support to help them design and develop their robotic systems. More in particular, for the following aspects: requirement specification; best practices in the design of reusable building blocks; and (semi)automatic software generation, testing, and validation.

The suggested solution direction ("Model Driven Engineering") can sound rather traditional at first sight, but its focus on the development of a methodology for making "reusable models" in the high-complexity context of robotics yields a set of software engineering research challenges that are not encountered in other ICT-driven domains.

Planning

- **3 years:** an "upgrade" is realised from the current MDE methodology (and ICT tools) in mechatronics to the context of robotics. This upgrade consists of (i) creating models for robotics-specific components such as perception, planning and world modelling, and (ii) system-level methods to integrate such components into robust, safe and predictable systems.
- **7 years:** models, tools and methodologies are realised to support the "new" kind of interactions that are required in robots that have to act reliably, safely and efficiently in the targeted application domains. The major challenges are on how to model, program and coordinate the (not only physical) interactions between, and behaviours of, several robots operating in the same environment, each possibly with a different task. In addition, a systematic methodology is required to help engineers design, develop, test, deploy, and operate such "systems of autonomously interacting systems".
- **10 years:** compared to the 7 years' goal, the additional challenge consists of developing and supporting also human behaviour and human-robot interaction models, physical as well as social.

6.2.2 Subject 2: Task-centred robot programming: from "how?" to "what?"

The previous research line targets the developers of robotics software systems, but those developers are only half of the story: progress must also be made to support the users of such systems. More in particular, expert users in the mentioned application domains must be given methods and tools to program their robot systems using only domain-specific models. That is, those experts should be allowed to programme "what" the robots should do, using terminology, templates and models that are comprehensible to human experts in the domain.

The suggested solution direction is "semantic modelling of application domains": the concepts, terms, relationships, actions, skills,... that human experts use to solve problems in a certain application domain must be formalized, in computer-readable and -processable formats, such that robots can be programmed in the semi-natural languages that domain experts use to talk to each other.

Planning

A methodology of "knowledge extraction" from domain experts is developed, such that semantic meta information can be formalized, reasoned about, and exploited in the robot programming. The following phases are envisaged in this research challenge:

- **years:** the "motion" aspects of robots are semantically modelled, and made available as a "programming language".

- **7 years:** the "task" aspects are semantically modelled, and made available as a "programming language".
- **10 years:** a methodology (including software tool support) is created with which the domain experts themselves can realise the above results.

6.3 Contributors

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7 Safety for Service Robots

7.1 Introduction

In order to successfully exploit a service robot, guaranteeing dependability of the system is one of the main requirements. Dependability is an integrated attribute that consists of safety, availability, reliability, integrity and maintainability. Safety is an essential component of the dependability requirement including safety to human beings, the robot itself and the physical environment.

Like any product that is to be released to the user, robots will require a certification before they are put to use. The base of the requirements to obtain the certification is defined in standards together with acceptable design guidelines and verification techniques/evidence. When it comes to safety standards, they define:

- Safety requirements – set of requirements/norms appropriate for safe operation
- Design guidelines – lists of correct methods for system design and implementation
- Validation and verification techniques - methods to test whether the requirements and guidelines are applied properly

Different application areas have very different safety requirements for robots. Space and military robots are very different from domestic or professional service robots, and manufacturing robots are again different. To focus the discussions, we decided to restrict ourselves to service robots. Together, professional and domestic service robots are the fastest growing fields of robotics, as analyzed by the IFR (International Federation Robotics). Furthermore, especially in service robots the human – robot interaction with non-trained consumers will be one of the most challenging aspects of safety. These users might even have physical or mental disabilities.

7.2 Analysis, Focus and Planning

For the analysis of the challenges, solutions and to define a plan, a working group has been formed consisting of experts from the Dutch industry, academia, and research organizations. From their experience, this group gathered the challenges that are present in the field of safety for service robots, but also the available knowledge and solutions in the Netherlands. Next, a plan was created to approach the remaining challenges, for which solutions are not yet available.

The challenges in safety for service robots have been grouped into three themes: User, Regulation, and Technology. In the next sections, we will explain what safety means in these themes, and discuss the challenges and solutions.

7.2.1 Subject 1: User

Context:

In a robotic system where human interaction is involved with a certain risk, it is important to carefully design the robot, taking into account the famous Murphy's law: "If something can go wrong, it will". When interacting with human, it is very important to understand the human behavior and human perception of the robot behavior. Especially as there are different types of users: professional and non-professional, trained and non-trained, healthy and fragile, and are often very different across the various application domains.

Challenges:

- Creating systems that (professional) users can trust
- Making models about user behavior
- Intuitive user feedback methods to indicate motion paths of the robot and preferred motion paths for the human
- System that complies to and sets priority to user requests

Available solutions:

- In many industrial and academic projects knowledge has been gained on user behavior, in many different application domains
- Some of this knowledge on user behavior has been formalized in available standards
- At various organizations there exist facilities to carry out realistic simulations or controlled tests in realistic environments with real users
- Various consortia exist of user groups, in research as well as in industry

Current work:

Current work can be found by browsing for human-machine interaction on www.robodb.org.

Key players:

IE&IS group of the TU Eindhoven, Philips, Focal Meditech.

7.2.2 Subject 2: Regulation

Context:

Industrial robots are the most widely used robotic application for decades. This application area has a number of regulations and standards from national as well as international organizations. Little was done when it comes to safety standards of service robots until recently. Also in the robot work space - which is not recommended in industrial robotics standards where safety is primarily ensured by separation - various activities are initiated to define standards for physical interaction of humans with robots. The ISO has started to revise the industrial safety standards to incorporate more human interaction. Furthermore, they have formed a new working group to define new safety standards for personal care robots, ISO/DIS 13842 ‘Robot and robotic devices – Safety requirements – Non-medical personal care robot’. The ISO safety standard for personal robotics is expected to be released mid 2012. Other countries such as Korea and Japan have started to work on regulations and standards for personal robots as well.

Challenges:

- Procedures (especially decomposition and allocation of safety aspects/certified components) to follow and document to achieve an appropriate level of certified safety
- Availability of knowledge on safety requirements for a consumer service robots: e.g. mechanical, dynamic behavior, and electrical
- Classification of robots and robot applications for safety requirements
- Robot must not harm humans, but accidents can happen
- Procedures to learn as much as possible from accidents (and near accidents) in this emerging application field

Available solutions:

- ISO working groups established on care, medical and transport
- Norms from other communities like industrial robots and household devices
- Survey on safety in domestic robotics
- Expertise from medical safety regulations can be applied to service robots as well

- Risk management models, incident analysis methods

Current work:

- ISO 13842 norm on safety requirements for non-medical personal care robots is expected mid 2012.

Key players:

ISO, NEN

7.2.3 Subject 3: Technology

Context:

Creating a safe system by eliminating or reducing possible risks is the core issue in safety and it, by itself, is an iterative three step process that includes: Safe design to avoid or minimize possible risks, a protection mechanism for risks which cannot be avoided by design, and finally a warning to the user in case both design and protection failed (preferably with instructions to minimize the size and consequences of the accident).

Safety in mechanical design and actuation deals with the crucial issue of ensuring inherent safety, i.e., safety even in the unlikely case of loss of the entire control system. I.e. manipulators suitable for domestic robotics are designed to be lightweight and compliant so as to mitigate any possible injury that may arise in case of uncontrolled collision with human. Safe mechanical design comes at the expense of performance so an appropriate trade-off between safety and performance should be made in design innovations.

A robot as an intelligent safe system should intrinsically be able to handle uncertainty in its model of the environment. In order to deal with the uncertainty, a domestic robot should be equipped with a range of sensors including proximity, force, tactile, vision, sound, and temperature. Increasing the type and number of sensors gives redundancy to the system and yields an improved environment model, while at the same time increasing cost and complexity.

Challenges:

- Tooling for safety
- Attentions for safety during development, but this should not be blocking
- Intrinsic safety design
- (Asynchronous) control structure for decision making
- Sub systems safety for manipulation
- Sensor (fusion) technology for use in medical applications, e.g. operating room
- Collision detection sensors that can cover the complete surface of robot
- Environment mapping for safety
- Prediction of movements for collision prevention and warning
- Practical double safety systems

Available solutions:

- Methods and tools from other communities, e.g. medical
- Energy based safety metrics
- Sensor technology for safe movements
- Low cost 3D vision sensor technology from gaming computers
- ROS (Robotic Operating System) for sensor fusion in domestic robots
- Environment mapping techniques

Current work:

- Many projects in research and development are integrating advanced sensor technology in their robots. From all these projects, lots of derived knowledge can be directly applied in the safety system of the robot. Also here, www.robodb.org gives a good overview of the available technology R&D in the Netherlands.

Key players:
See www.robodb.org.

7.2.4 Planning

From the above given challenges and available solutions, the goals were derived what we should work on in the near and longer future. For the three aspects – user, regulation and technology - these goals are grouped in short term, mid term and long term goals, in the following table:

	Short term	**Mid term**	**Long term**
User	Domain specific user behavior from experience; acceptance: Marketing strategy, communication, image; acceptance: Perception of safety methods and criteria		
Regulation	Classification; Extend current regulations based on new technology; Scan on what's already available in the world and analyze the gap using forecast model;		Harmonized law; Second loop learning: system for constant feedback from existing applications in the service field to (re)design of new/improved systems
Technology	Proximity sensing; Vision for safety; Collision detection and prevention; sensor fusion/ probabilities; environment maps	Frameworks to guide safe designs; Decomposition of safety implementation; Compliance in mechanics	Robot feel

From the complete analysis described above, we derived the plan to *develop a safety framework for service robots*. This includes:

- Describing use cases of potential hazardous situations and what should happen in these situations, from a user perspective.
- Develop a set of guidelines, components, software constructs etc. that can be reused across projects. Ideally, these software components have been tested in real-life situation along with some guidelines on their pro’s and con’s. Simple examples could be:
    1. How to attach the red-alarm-button on a robot to disconnect the power supply from the robot.
    2. The development of a speech module with a number of key words that can be used at all times to stop/move/control a robot in emergency situations. This module should always be running and have a high priority.

- Previously, for (less-intelligent) systems (e.g. cars), a lot of these constructs and safety methods have been developed. These should be adapted to service robots, which are however a lot more intelligent.
- Safety also means perceived safety. Users of the robot should always have a “mental model” of what the robot is doing, to always understand the current actions of the robot, and to be able to predict what the robot will be doing next. A robot that is doing unexpected actions, will give an unsafe feeling.

7.3 Conclusions and Recommendations

Safety in service robots is increasing rapidly in importance, as in all domains service robots are operating more and more in the vicinity of and in close cooperation with humans. The safety in the robot should take care of avoiding and handling hazardous situations to reduce the severity and likelihood of harm to acceptable levels.

Safety is one of the critical issues that must be guaranteed for successful acceptance, deployment and utilization of service robots. Unlike the barrier based operational safety guarantee that is widely used in industrial robotics, future service robots have to deal with a number of issues such as intrinsic safety, collision avoidance, human detection and advanced control techniques.

The analysis in this chapter presented the current challenges for safety in service robots, but also what we already have to offer. These have been subdivided over three themes: Human, regulation and technology. These three perspectives cover the main aspects that should be consulted when dealing with safety for service robots.

From the analysis, a plan has been derived to *develop a safety framework for service robots*. This framework should help the developers to ensure safety at a sufficient level, according to standardized regulations (norms), allowing easy adoption by the different stakeholders. The framework should be developed based on available knowledge and use-cases, preferably in a separate dedicated project.

7.4 Contributors

The following individuals have contributed to this chapter (in alphabetical order):

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8 Education

8.1 Introduction

Robotics will be of increasing importance in the near future in the application fields Care, Cure, Manufacturing, Domestic services, Household services, Agro & Food. The impact on thinking about technology, its users and its stakeholders will change dramatically. This will lead to a strongly increasing demand for knowhow with respect to:

- how will human beings interact with robotics
    - applicant/operator
    - patient/client
- how to apply robotics in the above mentioned fields
- how to define robotics for the user in the
- how to design/engineer and manufacture and maintain robotics

The increasing knowhow demand will not only lead to research on subjects related to the items mentioned above and their interaction; it will of course also have a strong impact on education.

8.2 Analysis

As indicated in the introduction, the wide impact of robotics will lead to changing requirements with respect to education. This will start on the primary levels up to the post-master levels of education. It has not only impact on the involved disciplines itself, both on applicants side and on the side of the technology disciplines. More than on the individual disciplines it will have a huge impact on multidisciplinary ways of teaching. Within robotics e.g. mechatronics e.g. is one of the involved multidisciplinary technology disciplines integrating primarily mechanical, electronics, technical software insights and thoughts. In robotics this is far from enough. Integration of application disciplines (e.g. cure/medecin) , psychology (user-robotics interaction), product management (product/service definition) will be a must in order to be successful in making robotics successful in general. This means that multidisciplinarity will have to be much wider defined than nowadays and it will be a big challenge to get teachers and students getting accommodated to these new way of thinking/working. since the robotics landscape is changing rapidly also post graduate courses and trainings will be necessary.

These thoughts were the background for Roboned to found a robotics education cluster in order to come up with advices with respect to education on robotics.

8.2.1 Matches and Gaps

In a workshop on November 2nd 2011 education on robotics was discussed with several people involved in the field of robotics application and education.

In this workshop it was mentioned that technology push is a risk. E.g. Buying robots and applying them instead of designing/building them by yourselves can also be a valid choice for application innovation incl. the belonging education. At this moment it is felt that education in the robotics backgrounds is ok; more attention is needed for the application fields of robotics. Introducing

“Creative technology”; making connections between several fields of technology and applications, would strongly enhance the innovative power of the next generation students. Multidisciplinarity wider than the technology fields is a must; especially in educational projects with involvement of several faculties this could be implemented.

Summarizing several opinions from this workshop with respect to matches and gaps related to robotics education on one and success in robotics on the other side:

Matches:
- technology education ; technology subjects
- education on individual discipline level

Gaps:
- multidisciplinarity necessary for setting up successful applications
- cooperation between disciplines withheld by discipline-oriented faculties/departments
- application knowhow versus knowhow for designing/building robotics
- integration of robotics in continuous learning trajectory from primary school up to (post-) university level
- technology push vs. technology pull

Thus the Roboned workshop on November 2, 2011 helped the education cluster to focus its work.

8.3 Focus and Planning

The Roboned education cluster has started its work by the end of September and has defined its goal as follows:

Goal cluster Roboned Education:
The Roboned initiative plans to make an inventory of the education in the field of robotics in the Netherlands. The education cluster (members appointed) will make an inventory of the education in bachelor and master tracks. We will start in the technology education area but preferably we will also make an overview of the education in robotics application areas such as agriculture, cure and care in a next stage . Starting in (post-)bachelor/mastertracks in technology-orieneted education has a practical background since the majority of robotics education takes place within this field nowadays . In next stages also the other education fields and levels will be subject of inventory for the education cluster. The inventory we already started will give an overview which can be compared with the technology needs as defined in the roadmap of the agriculture, manufacturing, cure, care and household Roboned clusters. Thus an advice can be derived for further improvement of robotics education in the near future.

In the first round of analysis the education cluster has made a restriction in order to focus :
- universities of technology/agriculture
- universities of applied science; technology/agriculture
- postgraduate education for both mentioned levels

This implies that following subjects will be analyzed in a later stage:

- Inventory of robotics application education in non-technical studies in bachelor and master tracks:
    - Cure
    - Care
    - Domestic services
    - Social sciences
    - other
- Inventory of robotics education on other technical levels (esp. "MBO"-level

Similar accounts also for:

- Secondary level education
- Primary level education

The education cluster has started an analysis of the education subjects and projects in robotics. We intend to set up a matrix with application and technology subjects/projects on one axis and the universities/institutes on the other axis.

The application knowledge subjects/projects will be linked to the 6 application clusters in Roboned; agro&food, cure, care, domestic services, professional services and manufacturing. The technology knowledge we will set up with help of our best practices and our favourite robotics literature. With help of these items/subjects we will set up a matrix with the necessary knowhow items; technology and application oriented)

The other axis of the matrix will be filled with the institutes/studies:

- Involved universities:
    - Wageningen, Nijmegen, Groningen, VU plus UvA, both in Amsterdam and 3 Universities of Technology,
    - Universities of applied science;
- Post-graduate courses:
    - The High Tech Institute/techwatch
    - ESI
    - PAO
    - Engenia
    - by universities (of applied science)
    - in-company (e.g. Philips)
    - other

The matrix will also be discussed with representatives from the application clusters and thus be completed from the knowledge demand side including the demands derived from the application roadmaps. Special attention will be paid to the multidisciplinary training of students (in fact all stakeholders!! So also teachers and other participating persons). Thus an education roadmap with advised improvements/new subjects/project formats can be put forward.

When completed the matrix it must be maintained and can act as a virtual study guide with respect to robotics themes including classification entrance levels and end levels (bachelor/master/post-bachelor/post-master) It is also advisable to have this small committee working on monitoring the follow up/refreshing of the set of advices which have been put forward.

The inventory is concentrated on (post-) bachelor and (post-)master education levels concentrated on the technology-related areas. We realize that this is not sufficient; Below you will find the other fields which will need as much and separate attention when having finished the first priority

The order of priority for making this type of inventories is:

- Inventory of robotics education in technology tracks on bachelor/master and postgraduate level
  The first priority of the education cluster is to make an inventory of the robotics related education items within the Netherlands:
    - Inventory of robotics education in bachelor and master tracks
    - Inventory of robotics education post-bachelor and post-master
- Inventory of robotics education in non-technology tracks on bachelor/master and postgraduate level
  Education with respect to application of robotics is an important factor for the acceptance of robotics and also to change the technology push into a technology pull situation. The education cluster can continue its work in following sectors when having finished the first priority work:
    - Cure
    - Care
    - Domestic services
    - Social Sciences
    - other
- Inventory of robotics education in tracks on all other levels
    - Of course the inventory with respect to robotics education will not be complete without a further roll out of the inventory:
    - Inventory of robotics education on other (technical) levels (esp. “MBO”-level
    - Inventory secondary level education with respect to robotics education
    - Inventory primary level education with respect to robotics education
    - Other:

Remark: In all cases several types of robotics education will be part of the inventory:

- Man-robotics interaction
- Research/Design/manufacture/service related to robotics
- Application of robotics

8.3.1 Planning

- Short term Goals= Status of subject in 1 year (2013)
    - Matrix of subjects/projects on (post-) bachelor and master levels versus universities/institutes: Feb/March 2012
    - Matrix discussed with application cluster representatives: May/June 2012
    - Advice with respect to robotics education/roadmap: September 2012
    - Matrix extended and set up is sustainable/monitoring follow up of roadmap: December 2012
- Mid term Goals= Status of subject in 3 year (2017): no planning information available yet
- Long term Goals= Status of subject in 10 year (2022): no planning information available yet

8.4 Conclusions and Recommendations

Work on education roadmap for technology bachelor/master and post-bachelor/post-master tracks is in progress. Other education levels or robotics education in non-technology tracks will be picked up after this first stage. It can already be advised that:

- Attention for multidisciplinarity in subjects and projects is strongly necessary;
- Sustaining of the matrix set up for the (post-)bachelor/master educational level will be sustained/maintained by a small/dedicated group when the matrix is “ready”. The education cluster has the opinion that it is important to make the matrix such that it can be actualized relatively easily. It can also be a point of discussion whether such a committee may obtain an extra task in the future in validation/certification of robotics education modules/subjects;
- Monitoring/refreshing the conclusions/advices of the Roboned Education cluster will be a must on a regular basis after having finished the first advices/roadmap;
- The set up of an inventory for other educational tracks (non-technical, other technical levels) will be carried out by a (partially) renewed education cluster;
- For all work it will also be interesting/necessary to check what is going on outside our country. We will discuss with Roboned whether e.g. the European Robotics Association or other (e.g. Japan, Korea, China, USA) have made similar education roadmaps with respect to robotics education.

8.5 Contributors

The following individuals have contributed to this chapter (in alphabetical order):

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9 Ethical, Legal and Social Issues in Robotics

In this chapter we will discuss possible ethical, social and legal issues that may arise when robotics proliferates in various spheres of everyday life in the Netherlands.

9.1 Introduction

Developments in robotics technologies have undergone significant growth in the past decades in many different areas, and these technologies are currently finding an increasing diffusion in different spheres of everyday life, ranging from the workplace (manufacturing, collaboration with human workers) to private homes (service and care robots), and from the transport sector (autonomous vehicles) to environmental monitoring, crowd-control and warfare (drones). In each of these areas, the deployment of machines raises myriad ethical, legal and social questions. In some cases, these issues revolve around humans' interactions and cooperation with humans, in other cases they arise due to the fact that robots may take over tasks that were previously conducted by humans. In either case, the ethical, legal and social questions that emerge in light of advancements in robotics, which we have clustered under the abbreviation 'ELS' (Ethical, Legal, Social), require timely legislative action, but also broad societal discussion, in order to facilitate the development of humane robotics and to foster support for the development of this new market.

9.2 Analysis

When robotics technologies will be deployed in the various domains mentioned above, investigating the social, ethical and legal consequences this may have is not a straightforward enterprise. This is so, because different social standards, ethical norms and legal rules govern all of these domains, and hence the legal, ethical and social issues raised in each of these contexts need to be addressed in the near future. What's more, different robotics technologies *within* the same context also raise different ethical, legal and social issues, which each need to be addressed individually. However, there are also a number of themes that span, or run through, all of the domains in which we may encounter robots in the (near) future, for example regarding the social acceptance of robotics technologies, or revolving around questions of liability and responsibility when robots are deployed. In this chapter we present a set of themes that addresses legal, ethical and social issues on this more general level. Because of their level of generality and applicability to all domains of robot use, these issues are most pressing to address: they are likely to appear in a wide range of social contexts when robots are deployed on a large scale.

Below we present an overview of the ELS issues that are likely to appear on the horizon, either in the short term or in the longer run. This overview is based on the joint work of a group of ELS experts, representing almost all institutes and research groups working in this field in the Netherlands. After discussing the most important ELS themes (section 2.2.1), we will present ideas that may contribute to their solution (section 2.3), along with a timeline for both the problems and the solutions to appear (section 2.4).

9.2.1 Themes

The first ELS theme that needs to be addressed within the robotics industry and in science, but also by policy makers, politicians and the media, is that of the **social acceptance** of robots in society. Let us begin by pointing out that social acceptance is, in fact, not an ELS *problem*, but rather an ELS *goal* – to safeguard the widespread use of robots societies must ensure that these machines are socially accepted and acceptable in various contexts, both to individuals and groups of humans working/interacting with them. Hence, scientists, industry, policy makers, politicians and the media all need to be aware of the role they play in creating and proliferating images of robots and robotics. Careful and sensible positioning of the benefits *and* risks involved in deploying robots in society can contribute to a positive, trustworthy image of robots, and should thus be strived for.

A second theme of great importance to be addressed is that of **liability, responsibility and security**. If robots are going to be deployed on a large scale, and will enter the everyday lives of human beings in various forms, then we must think through the legal consequences thereof: who is responsible when a robot causes damage to property or a person? How can we ensure that the risk of being held liable does not hamper innovation, and how can we balance risk and security in experimenting with new (forms of) robots?

Third, it is vital that we investigate the ways in which **social practices and social relations** may change as a result of introducing robots into them. How do social practices change when tasks are delegated to machines, and how does this affect the social relations between humans in these contexts, and between humans and machines? For example, when delegating the task of lifting and moving patients to a robot, the care practice is deeply changed, both in a practical sense (the caregiver now focuses on (operating) the machine rather than the patient) and in a relational sense (physical contact is no longer an aspect of the interaction between caregiver and patient). Though such changes may appear to be small and insignificant on the surface, they alter situational patterns of interaction in ways that may sometimes have unintended, and negative effects. Therefore, we need to carefully plot scenarios that investigate such changes at various levels of abstraction, from the macro level (rethinking the delegation of the central tenets of healthcare in relation to robots) to the micro level (as in this example).

Finally, and building on the previous point, we need to investigate the ways in which **core values** in our society as a whole, and in the various spheres of life into which robots will enter, are affected by their advent. Think for instance of the ways in which using robots in the home may have a bearing on individuals' privacy, or what it means to delegate control over a wide variety of tasks to machines.

9.3 Focus and Planning

9.3.1 Subject 1: Social acceptance

Context: When robots enter different spheres of life, ranging from healthcare to the home, and from factories to traffic, it is important that humans *accept them* – as a new workforce, or as aides, to which responsibilities and tasks can be delegated. Social acceptance and social acceptability may be hampered for various reasons: humans may feel 'replaced' by machines, they may feel threatened in their job security because their jobs will now be delegated to machines, or they may feel 'dehumanized' by medical care received from a machine rather than a fellow human being.

Moreover, pessimistic science fiction stories of robots surpassing human beings (and ultimately destroying mankind) may lead to fear and negative responses to their appearance in various social contexts.

Central issues: One of the most important ways in which to facilitate social acceptance is to *manage expectations*: ensuring that individuals and groups interacting with these machines, or working alongside them, will know their strengths and weaknesses, and will understand what these machines, and the science that underlies them, can and cannot offer. Second, and in close connection to the above, to promote social acceptance it is important to have an open and wide-ranging *public debate* on the roles of robots in our (near-)future society, and on the social and ethical implications this has. Only if stakeholders from industry, science and politics put their cards on the table with regard to the introduction and deployment of robots in society can the public learn about the pros and cons of the use of these machines, and hence come to a balanced perspective on, and optimal acceptance of, robots as future 'partners' in various domains in everyday life.

Solutions: The social acceptance of robots would greatly benefit from *involving non-roboticists* (policy makers, ethicists, and, most importantly, end users) in the design and development process of these machines. This would strengthen the chances of creating machines that would meet the *contextual societal needs* of the individuals that will work/interact with them, thus improving the chance of a smooth introduction and easy acceptance of these machines in each context. A second solution that may contribute greatly to social acceptance would be for the robotics community (science/knowledge institutes, industry and government) to initiate a campaign *debating visions of the future* in relation to robotics. Currently, the general public tends to believe that robots are either an ideal or a threat, but in any case a development of the far, far future. What's more, most people believe that robots will predominately have a humanoid form – when they do not have such a form, they are hardly recognised as robots in the first place. By reporting on the current developments in robotics, and engaging in debates over their future role(s) and capabilities public awareness would rise, and this would also facilitate social acceptance.

Current work: The Rathenau Institute in The Hague is conducting a study on new robotics, which includes the issue of social acceptance of robots in various spheres of everyday life. When this study is completed, the Rathenau Institute will advise politics and government on engaging in the public debate proposed here. The Strategy Department of the Ministry of Security and Justice has addressed social acceptance as an important issue when introducing robots for purposes of security and justice in the public domain. Finally, researchers from the Donders Institute for Brain, Cognition and Behaviour (Radboud University) and from the Philosophy Department at TU Twente are also conducting research on the social acceptance and social acceptability of robots in various everyday domains.

Key players: Rathenau Institute, Strategy Department of the Ministry of Security and Justice (MinVenJ), Donders Institute, Philosophy Departments of Universities.

9.3.2 Subject 2: Liability, responsibility and control

Context: When robots will proliferate in everyday contexts, accidents are bound to occur as well. Robots may accidentally hurt or harm humans or their property, they may run haywire or they may be misused or mishandled by humans. Whenever damage occurs, questions of liability and responsibility arise. Currently, it is unclear for industry and research groups in the field of robotics how liability issues may play out. This obstructs innovation in a serious manner, because companies and research groups are hesitant to develop cutting edge new technologies, since this increases the risk of being sued for damages when things go wrong.

Central issues: Different scenarios can be envisioned here: robots could simply fall under the existing framework for *consumer law*, which prescribes that manufacturers and/or businesses are responsible for the robot's proper functioning (and hence liable when they malfunction). However, since robots become ever more complex, and consist of numerous subsystems to which many research groups and companies contribute, some legal scholars believe that this system cannot hold in the longer term. They propose, instead, that liability issues in relation to robots ought be fall under a so-called *strict liability regime* (in Dutch 'risico-aansprakelijkheid'), whereby the owner of the machine is responsible for the damage caused by the machine, similar to the ways parents are responsible for their children's actions, or employers for their employees' actions.

Solutions: To meet the challenges with respect to liability, responsibility and control three central steps are proposed. First, legal scholars need to create an *inventory of applicable law*, and investigate whether existing legal frameworks apply, and/or need adjustment in light of robotics developments. Second, to stimulate innovation robotics developers and businesses should receive improved protection from lawsuits through the creation of *insurance policies*. New insurance packages could be created, or existing insurance could be adjusted, in cooperation with insurance companies. Third, it would be highly beneficial to robotics developers and businesses if, somewhere in the Netherlands, there would be a so-called '*free zone*', an area in a city or town, where robotics developers could test new robotics technologies in the real world, without immediately running the risk of receiving liability claims. Such a free zone would enable them to experiment extensively with new technologies prior to placing them in the market, hence insulating the larger public from risks that may occur when no such experimenting in real-world settings has taken place. High tech cities such as Eindhoven or Enschede would be ideal candidates for the creation of such a free zone, and hence these cities ought to be engaged in a debate about this idea first.

Current work: The Tilburg Institute for Law, Technology and Society (TILT) of Tilburg University will start with a two-year European-funded FP7 project on Robotics and Law (RoboLaw) in the spring of 2012, in which liability and responsibility are central themes. The Center for Intellectual Property Law (CIER) of Utrecht University and Donders Institute for Brain, Cognition and Behaviour (Radboud University) also conduct research in this area.

Key players: Institutes for (property) Law, Donders Institute.

9.3.3 Subject 3: Social practices and social relations

Context: In the past decades, research in engineering, human-computer interaction and philosophy of technology has consistently revealed that when technologies are used in social practices, these practices tend to change because of their use and/or presence. For example, using telephones to communicate over longer distance has changed the way in which humans interact in comparison to face-to-face communication. Similarly, using social network sites to maintain or instigate friendships leads to different forms of connection, and different expressions of friendship, when compared to friendships conducted in the real world. It is safe to assume that this fact will also apply to robots when these will start being deployed on a large scale in various social practices and contexts. However, at the moment we do not have a solid grasp on *how* social practices, e.g. in healthcare, in traffic, or in the home will change exactly because of the introduction of robots into them.

Central issues: The central issue relating to this theme is the fact that adding a robot to a professional/social situation will change that situation: it will change the roles people have in these professional/social situations, and the relations between participants in these situations. What needs to be clarified, on a case-by-case basis is exactly *what changes will be brought about*, whether or not these changes are acceptable or desirable, and if they are not, what procedures or *design features* can be used to ensure that social/professional practices and the social relations in them will not be affected in a negative way.

Solutions: One of the key solutions in this area revolves around creating a *design approach*, in which a thorough understanding of the outcomes of different design choices, in terms of their impact on social practice and social relations, will become standard practice. This could be achieved through the use of scenarios as a design method, and through the deployment of multidisciplinary design teams, involving ethicists, social scientists and end users alongside engineers and designers. A second solution focuses more on the end-user side of things: in order for robots to find a proper place in various social practices, and ensure safe and sound use of such machines, end users (both in professional settings and in non-professional contexts) need to be *educated* about the do's and don'ts of human-robot interaction, about their possibilities and limitations. This would also contribute to the prevention of the unintentional and faulty use of robot, and of outright misuse.

Current work: Philosophers at TU Twente are currently conducting research on the way care values and care practices, and social relations are affected by the use of healthcare robots. The Rathenau Institute is also studying the way social practices are affected by the introduction of robotics in the project mentioned under 'Social acceptance'. Finally, the Strategy Department of the Ministry of Security and Justice (MinVenJ) has investigated the issues that need to be addressed when introducing robots into various professional/social contexts.

Key players: Philosophy Department Universities, Rathenau Institute, Strategy Department of the Ministry of Security and Justice (MinVenJ).

9.3.4 Subject 4: Core values

Context: When deploying robots in everyday contexts – for care and cure, in the home, in traffic etc. – this entails that these robots will dramatically increase their level and intensity of interaction with human beings. Combined with the fact that we delegate more and more tasks to machines, this raises questions surrounding the core values that we hold dear as a society in each of these contexts. In healthcare contexts, for instance, we need to consider which tasks we can delegate to machines without negatively impacting respect for bodily and emotional integrity or undermining autonomy. Similarly, in the home we must ensure that we do not invade humans' privacy to an unacceptable degree.

Central issues: When developing and designing robots it is crucial that we come to a better understanding of the way the *form* (appearance) and *functionality* of particular robots affect both their perception by humans and their scope of tasks in specific contexts.

Solutions: The solutions for this theme largely overlap with those proposed under the previous heading: it is important that design and development of robots takes place in multidisciplinary teams, using scenario-based approaches. One practical idea with respect to solve perceived transgressions of core values by individuals in various everyday situations is to equip all robots with an 'emergency brake', which humans can use when they feel the robots crosses boundaries it shouldn't cross.

Current work: Several researchers at the Philosophy Department of TU Twente, at the Donders Institute (Radboud University) and at TILT (Tilburg University) investigate the ways in which norms and values are affected, on a contextual level, by robots and their use. Finally, this theme is also part of the Rathenau's study on new robotics.

Key players: Philosophy Department Universities, Donders Institute, Institutes for Law, Rathenau Institute.

9.3.5 Planning

Important contributions towards solving the themes addressed above ought to be made within the next 10 years. We have prioritized these themes as follows: although all themes presented here are urgent enough to require immediate commencement (and in fact, they are already under way), some can be resolved sooner than others. This is the overview of their duration and expected time of completion:

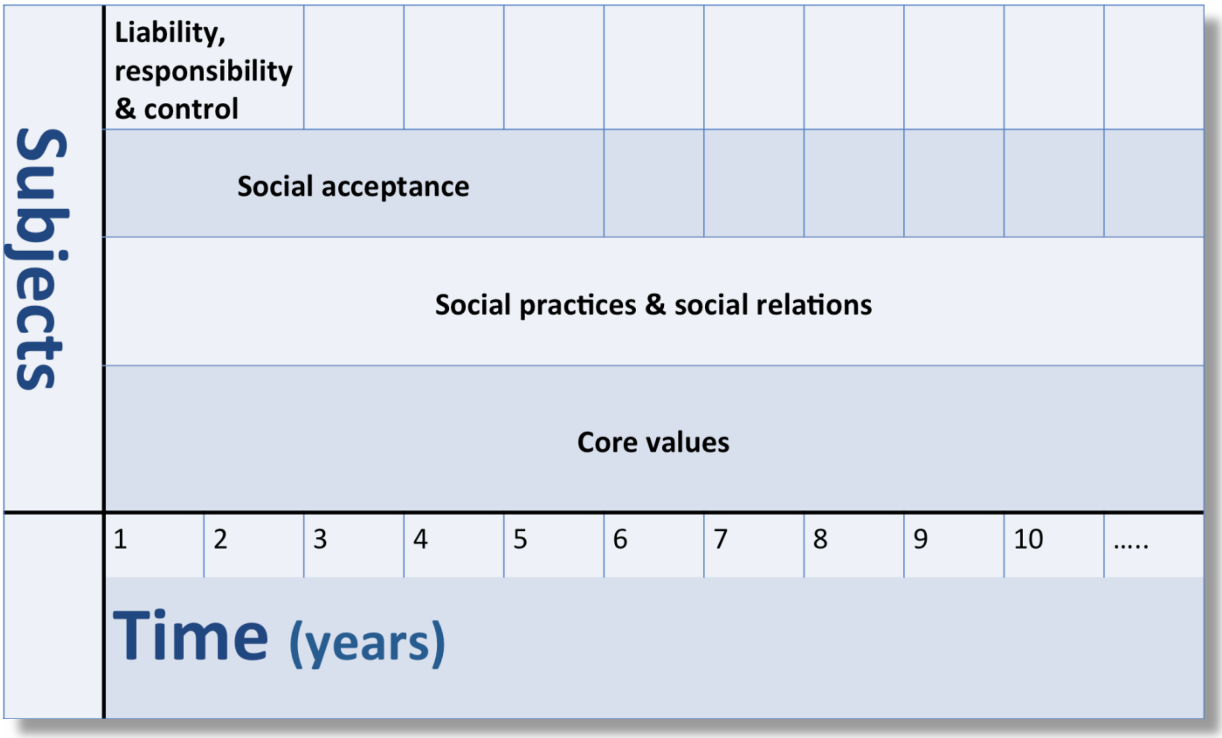
- Short term Goals:
    - **Liability, responsibility and control** is one of the most tangible issues, and it requires immediate and speedy action in the interest of innovation. Within the next two years legal scholars and regulators should create an inventory of applicable law with respect to robot(ic)s, and instigate changes in existing laws and regulations if this turns out to be necessary. Moreover, within the same period legal scholars, regulators and insurance companies should start work on creating insurance for robotics researchers and businesses. Finally, within the next few years stakeholders from the robotics community should aspire to realize at least one 'free zone' for experimentation in the real world, in collaboration with local governments.

- Mid term Goals:
    - **Social acceptance** is the second most urgent topic to be addressed. Within the next five years roboticists should collaborate with ethicists, social and political scientists, and representatives from knowledge institutes such as the Rathenau Institute to work up an agenda for a large-scale public debate about the risks, opportunities, pitfalls and prospects of robotics as one of the next key technological developments in and outside of the Netherlands. Moreover, representatives from robotics business and science should actively engage in expectation management with regard to the public through information programs and education.

- Long term Goals
    - **Social practices and social relations and core values**: While research is already under way in some areas of robotics in relation to social practices (most notably care) and social relations, very little work has been done on others. Moreover, the underlying core values under investigation up to date also predominantly focus on the healthcare domain. In the next ten years a methodology needs to be developed to investigate the impact of robotics on social practices and social relations, both on a macro and on a micro level, for all contexts in which robots may appear, for example involving scenarios. This methodology must then be deployed to study effects in all social contexts and practices ranging from healthcare to the home, from agriculture to transport, and from the factory to entertainment. In each context the core values at stake must be explicated

(if they aren't already), and it must be established whether core values are affected, and if so, if this is desirable.

The image below provides an overview of the four themes addressed in this chapter, and reveals on a timescale when they should be addressed, and when solutions may be expected to materialize.



9.4 Conclusions and Recommendations

In this chapter we have presented an overview of four key ethical, legal and social (ELS) themes that the robotics community needs to address in the upcoming years. In the interest of innovation in robotics, and to support the deployment of robots on a larger scale, the theme that is highest on the agenda is that of providing clarity on issues of liability, responsibility and control. We encourage legal scholars to establish how lines of responsibility and liability play out when applied to robotics within the next few years, so that developers (both in science and in business) can calculate the risk of damages in a proper way when taking their robots (from prototypes to final products) into the real world. We have suggested that the creation of insurance for roboticists could be an important practical contribution to this problem.

Next, to ensure a smooth transition towards a future society in which robots find their place we must engage in a public debate, and provide proper education, on the possibilities and the risks of robotics. Scientists, businesses, policy makers and the media must stimulate an open culture of discussion on whether we want to deploy robots in various domains in the first place, and what such robots should and shouldn't do. Moreover, we need to manage expectations, removing false images of the absolute doom or utopia robots could create, and replace these with a more realistic perspective on robots' (current) capacities and imperfections.

Finally, we need to consider carefully how the use of robots in various social contexts will have a bearing on the relationships between humans in these contexts, on the ways in which (professional) roles are played out, and the core values that may be affected by them. This is a challenging task, since it requires very detailed, almost case-by-case analysis. Yet we believe that by developing a methodology to study the impact of robots on social practices from a scenario-based perspective, and using multi-disciplinary design teams for the development of new robots, this vital task can nevertheless be accomplished.

9.5 Contributors

The following individuals have contributed to this chapter (in alphabetical order):

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