Development of validation methods for the safety of mobile service robots with manipulator

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Summary

With the emerging ISO standard 13482 a safety standard for service robots will be available for the first time. The current draft of the standard provides detailed requirements for risk analysis and risk reduction for "personal care robots", but lacks specific instructions for the validation of safety. As validation methods are essential for proving the compliance of future robotic products with European directives, in this paper detailed validation requirements for mobile robots are developed with a special focus on the area of mobile manipulation. To ensure practicability of the validation methods, a setup with the reference system Care-O-bot® 3 for the practical evaluation of all requirements is presented.

1 Introduction

In the future, service robots will be used in various applications in private households as well as in public environments. In order to bring such robotic products onto the European market, manufacturers have to prove that their products fulfil all relevant safety requirements from European directives and their harmonized standards [1]. Besides a thorough documentation including hazard analysis and measures for risk reduction, this also implies the application of validation methods. Therefore, manufacturers are in the need of clearly formulated instructions for validation methods which are easy to apply to their robot systems.
The safety standard for personal care robots ISO 13482 [2], which is at the moment being developed by ISO committee TC184/SC2 [3] and will be published for the first time in 2013 still lacks detailed requirements for validation. For hazards such as collisions or the loss of dynamic stability only general methods like "measurement" or "practical test" are listed. Here much more detailed and specific instructions for practical and theoretical validation need to be developed [4].
ISO safety standards are structured in type A standards which contain general requirements and are applicable for all machines, type B standards which focus on a certain safety function or a limited group of machines and type C standards which deal with a particular type of machine (Fig. 1). With respect to this hierarchy it has to be taken into account that several general type A and type B safety standards also provide basic methods for validation. Due to their general nature these methods are in many cases not directly applicable to safety functions of particular service robots and instead give the user of the standard only a vague idea of how validation has to be done. Nevertheless, these standards need to be taken into consideration when developing validation methods so that new testing criteria can be created as a supplementation of the existing ones.

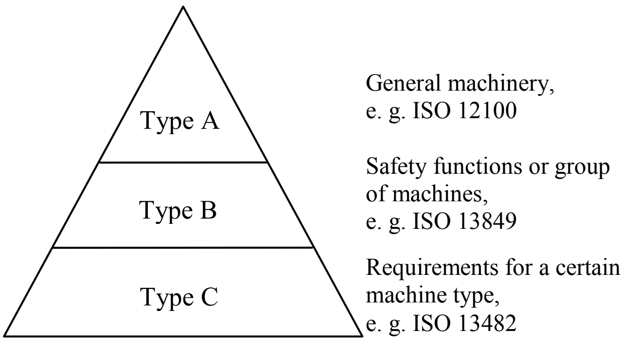

Fig. 1 Hierarchy of ISO safety standards

This paper gives an overview about existing validation methods in general standards and identifies gaps where new methods need to be defined (chapter 2). In chapter 3, the approach for the development of new validation methods in the area of mobile manipulation is described. Chapter 4 deals with the evaluation of these methods on an existing service robot. The paper closes with an outlook on the inclusion of the validation methods in future drafts of ISO 13482 and other standards.

2 Validation criteria in current ISO standards

As a type A standard ISO 12100 [5] lists hazards which are applicable for all kinds of machinery such as mechanical hazards (collision, instability, etc.) and electrical hazards (contact with life parts, etc.), but does not provide any validation criteria. Instead, many safety requirements can be found in type B standards dealing with a certain safety device such as pressure sensitive devices and optoelectronic sensing devices [6], [7]. Here validation methods only include testing of the device itself, but do not cover the correct integration into a service robot. Another source for validation methods are type B standards discussing general safety aspects of machines such as safety distances with respect to approach speeds [8] where validation methods for determining reaction times of sensor systems are defined. In these standards also only the sensor system itself is subject to testing whereas the use of these sensors in service robots is out of scope.

For safety related parts of the control system, type B standard ISO 13849-2 [9] applies. Here exhaustive validation methods for the reliability of the control system including failure rates, diagnostic coverage and the attended safety category by means of calculation and practical tests are provided.

Examples on how validation methods for a certain type of machine could be defined can be found in type C safety standards dealing with other machine types than service robots. The European safety standard for driverless trucks [10] provides for instance detailed requirements on what kind of probes have to be used and which tests have to be performed to validate the obstacle detection capability of a driverless truck.

The evaluation of existing safety standards shows that the future safety standard for personal care robots lacks especially validation methods for safety issues that are specific for service robots and their typical subsystems whereas validation methods for multipurpose safety sensors, control systems and general safety considerations are already available.

3 Development of validation methods for mobile manipulating robots

3.1 The need for additional validation methods

Based on the literature research to identify existing validation methods in the area of mobile manipulation, the need for additional validation criteria was determined. As validation is to a certain extent related to hazards, the approach of a hazard analysis was chosen to identify the new validation items. In a first step, typical tasks for mobile service robots with manipulator were identified based on the experiences with existing service robots [11], [12], which are:

- Moving and positioning of the mobile base
- Grasping, transporting and placing small objects
- Grasping and manipulating large objects with constraints (e. g. opening a door)
- Exchanging objects with a human

For these abstract tasks, a hazard identification was conducted against the background of a use in typical household environments, public places and industrial environments. The analysis showed that the main hazards for a person interacting with a mobile manipulating robot are impacts due to collisions as well as clamping inside the robot structure and being run over. This corresponds to the hazards listed in the current draft of ISO 13482.

In a second step, possible safeguards and control system functions for risk reduction were identified. For each of these measures the availability of appropriate validation methods was checked in order to identify missing validation requirements. As a result the following list of safeguards and control system functions were marked for the development of further validation methods:

- Detection of persons and other obstacles near the robot
- Avoiding obstacles by initiating a controlled stop or by performing evasion movements
- Detection of collisions, especially collisions with the robot arm
- Provision of an internal environment and obstacle model
- Provision of an internal kinematics model
- Safe transport of objects without dropping or spilling load
- Grasping with a sufficiently high grasping force and at the same time avoiding to injure body parts which might get clamped inside the gripper

3.2 Design of validation methods

The identified control system functions and safeguards have been further evaluated and an initial set of validation methods has been designed by the following methodology: For each safeguard or control system function in question, parameters were identified which affect the correct operation of these devices. In case of initiating a protective stop of the mobile base this includes ground conditions such as slope and friction whereas for sensing devices lighting conditions and temperature are relevant. In a second step, it was determined which kind of validation methods are suitable for ensuring correct operation of the mobile service robot together with the number of tests required to cover all possible influence factors. Finally, the necessary validation procedures were listed together with all relevant instructions. In case of practical tests, also the test environment and setup is described.

To keep the test setup for practical tests as simple as possible, test setups consist wherever possible of low-cost parts which can be easily bought or manufactured. In addition, it is tried to keep the number of tests and the required repetitions of these tests low in order to limit the overall costs of validation.

For the validation of obstacle avoidance capability, different “behaviors” of obstacles were defined (Fig. 2) that reflect the range of typical movements of dynamic obstacles such as a human in the robot workspace. Examples are static obstacles, obstacles moving towards the robot or obstacles crossing the way of the robot.

The current draft of validation methods for obstacle avoidance require, that for each obstacle behaviour three identical tests have to be conducted to verify, that the robot is able to either stop before touching the obstacle or to evade the obstacle. For these tests, typical environmental conditions shall be chosen and the velocity of the robot and the obstacles shall reflect the maximum velocity of the robot as well as the maximum reasonably foreseeable velocity of moving obstacles. Each test shall be conducted with different test specimen such as cylinders resembling body parts as specified in ISO 13856 [13]. With respect to household applications, a table shall be used as an additional test specimen for static obstacle avoidance, because it requires 3D obstacle detection capability to determine that the space between the table legs is obstructed.

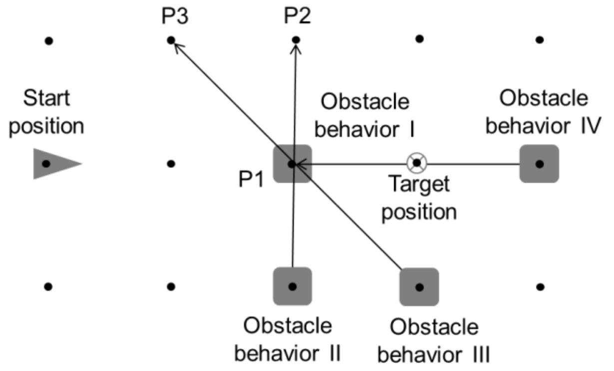

Fig. 2 Behavior of static (I) and dynamic (II-IV) obstacles used for validation tests

4 Practical evaluation with the reference system Care-O-bot® 3

In order to verify the practical applicability of the developed validation methods, a test setup with a reference system was created to ensure the following requirements are fulfilled:

- High reliability of test results
- Unambiguous results and a clear answer if all requirements are met
- Easy test setups that can be realized with low effort and low-cost material
- Reasonable number of validation methods and repetitions of tests.

The results of the practical tests with the reference system are used to further develop and refine the validation methods in several iteration loops. Only if the practical applicability of all methods is ensured, a proposal for integrating them in an ISO safety standard will be made.

4.1 The reference system Care-O-bot® 3

For practical testing the mobile household assistant robot Care-O-bot® 3 [12] (Fig. 3) is used as a reference system. The robot has an omnidirectional base consisting of four wheels that can be individually driven and rotated. The size of the base is mainly defined by the required battery space. Thus. the maximal footprint of the robot is approx. 60 cm x 60 cm and the total height of the robot including torso and sensor carrier is about 120 cm. The tor-so is directly mounted on the base and supports the sensor carrier, manipulator and tray. A SCHUNK LWA3 light-weight arm with 7-degrees-of-freedom is used as manipulator. It was extended by 12 cm to increase the work space such that the gripper can reach the floor, a higher shelf of the kitchen cupboard and of course the tray. A three-finger gripper with also 7 degrees-of-freedom is attached to the TCP of the light-weight arm.

Two safety laser scanners in the front and the back of the robot allow reliable obstacle detection in a plane of about 20 cm above the ground. They are directly wired into the safety circuit of the robot, such that all motors are stopped in an emergency situation.

For the safe operation of the robot, capable perception, navigation and manipulation components are required.

Perception components essentially comprise table-top object detection, 3D environment reconstruction [14] and person detection and identification [15].

The navigation component is responsible for navigating the robot in a collision-free way between two arbitrary coordinates in the map of the environment. The knowledge of the full map is however not required to ensure collision-free movements: the robot will try to dynamically adapt its path when a new obstacle appears on the path, even if it was not known at planning time. When the obstacle nevertheless enters the safety zones of the laser scanners (e.g. because of failure of the navigation component or because the object was moving too fast), the robot will stop immediately. Furthermore, a 3D obstacle map of the environment is generated from the 3D environment reconstruction component. When the robot moves, the complete configuration of the robot (i. e. the position of arm, tray and torso) is considered for the collision checks against the 3D obstacle map.

In order to increase the safety of the manipulator, several approaches are followed: Like for the navigation module, the 3D obstacle map is used to supervise the work space of the manipulator [16]. Thus, collision-free trajectories are ensured at planning time. However, we face the problem of occlusions, in particular through the robot's arm. Therefore, a second approach is pursued in addition: A tactile skin [17] integrated in the robot arm is used to detect collisions that have not been foreseen by the perception components. A safety related speed control for the arm is responsible for stopping the arm fast enough when a collision has been detected by the tactile skin.

Fig. 3 Household assistant robot Care-O-bot® 3

4.2 Practical tests

In order to test the validation methods on the reference system Care-O-bot® 3 a mechanism to move test specimen relative to the robot in a safe and reliable manner is necessary. To evaluate and compare test results, it is crucial, that this mechanism is able to move test specimen with a constant, predetermined velocity and that the position and velocity of the test specimen is synchronized with the movement of the robot.

To achieve this, a rail system equipped with an electric winch was developed (Fig. 4). The rail system has a height of two meters which allows the robot to drive under the rail without the rail itself being an obstacle. Test specimen are fastened to a cart pulled along the rail. A counterbalance on the other side of the rail tightens the cable and also allows moving the cart to be moved backwards. With a variable length of up to six meters, the rail system can be positioned in different orientations relative to the robot, such that for obstacle avoidance tests all obstacle behaviors shown in Fig. 2 can be simulated.

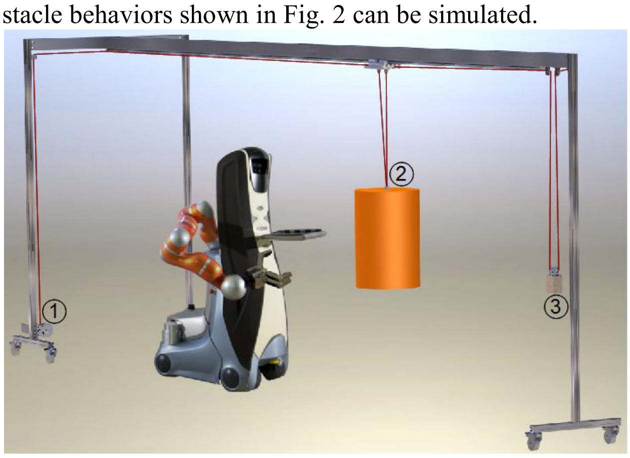

Fig. 4 Draft of the rail system for obstacle avoidance tests with winch (1), test specimen (2) and counterbalance (3)

The winch is moved by a servo motor which controller is connected to the software of the robot. The synchronization between robot and rail system is realized via the robot operating system ROS [18], [19]. This allows for example to determine the time between detection of an obstacle and stopping of the robot. To measure distances between robot and environment, the tests are further be recorded with an external camera system which is also synchronized with the robot.

5 Conclusion and outlook

Detailed validation methods are essential to evaluate the safety of service robots and to prove conformity with European directives and harmonized standards. Therefore, they are a prerequisite for successfully bringing new robotic products onto the market. As currently neither the applicable type A and type B safety standards nor the emerging safety standard for personal care robots provides detailed validation methods for mobile service robots with manipulators, new validation methods need to be developed.

In order to fill this gap, a risk analysis has been performed for typical tasks in public and household environments, safeguards and control system functions for which currently no validation methods exist were identified. In the next step, an initial set of validation methods for these safeguards and control system functions has been defined. The validation procedures are tested with the reference system Care-O-bot® 3 and will successively being optimized to ensure practical applicability.

Depending on the results the validation methods are discussed again and further developed to optimize practicability as well as their significance. In an iterative process, a final set of validation methods will be developed.

During the development process the new validation methods are regularly discussed with the technical experts of the ISO committee TC184/SC2 to gain additional feedback on the developed methods. In addition, the best way to include the validation requirements in the safety standard for personal care robots will be discussed.

6 Acknowledgement

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7 Literature

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