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Integrating Indoor Mobility, Object Manipulation, and Intuitive Interaction for Domestic Service Tasks

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***Abstract*— Domestic service tasks require three main skills from autonomous robots: robust navigation, mobile manipulation, and intuitive communication with the users. Most robot platforms, however, support only one or two of the above skills.**

In this paper we present Dynamaid, a new robot platform for research on domestic service applications. For robust navigation, Dynamaid has a base with four individually steerable differential wheel pairs, which allow omnidirectional motion. For mobile manipulation, Dynamaid is additionally equipped with two anthropomorphic arms that include a gripper, and with a trunk that can be lifted as well as twisted. For intuitive multimodal communication, the robot has a microphone, stereo cameras, and a movable head. Its humanoid upper body supports natural interaction. It can perceive persons in its environment, recognize and synthesize speech.

We developed software for the tests of the RoboCup@Home competitions, which serve as benchmarks for domestic service robots. With Dynamaid and our communication robot Robotinho, our team Nimbro@Home took part in the RoboCup German Open 2009 and RoboCup 2009 competitions in which we came in second and third, respectively. We also won the innovation award for innovative robot design, empathic behaviors, and robot-robot cooperation.

Fig. 1. Our anthropomorphic service robot Dynamaid fetching a drink.

I. Introduction

In order to leave industrial mass production and help with household chores, robots must fulfill a new set of requirements. While industrial production requires strength, precision, speed, and endurance, domestic service tasks require robust navigation in indoor environments, flexible object manipulation, and intuitive communication with the users.

Robust navigation needs a map of the home, navigational sensors, such as laser-range scanners, and a mobile base that is small enough to move through the narrow passages found in domestic environments. At the same time, the base must have a large enough support area to allow for a human-like robot height, which is necessary for both object manipulation and for face-to-face communication with the users.

Object manipulation requires dexterous arms that can handle the payload of common household objects. To detect and recognize such objects the robot needs appropriate sensors like laser range finders and cameras.

Intuitive communication with the users requires the combination of multiple modalities, such as speech, gestures, mimics, and body language.

While, in our opinion, none of the three requirements is optional, most available domestic robot systems support only one or two of the above skills. In this paper, we describe the integration of all three skills in our new robot Dynamaid, which we developed for research on domestic service applications. We equipped Dynamaid with an omnidirectional drive for robust navigation, two anthropomorphic arms for object manipulation, and with a communication head. In contrast to most other service robot systems, Dynamaid is lightweight, inexpensive, and easy to interface.

We developed software for solving the tasks of the RoboCup@Home competitions. These competitions require fully autonomous robots to navigate in a home environment, to interact with human users, and to manipulate objects.

Our team NimbRo@Home participated with great success at the RoboCup German Open in April 2009. Overall, we reached the second place. We evaluated our system also at RoboCup 2009, which took place in July in Graz, Austria. In this competition, our robots came in third and won the innovation award.

After describing the mechanical and electrical details of our robot in the next section, we cover algorithms and software integration for perception and autonomous behavior control in Sections III-VIII. In Section IX, we report the experiences made during the RoboCup competitions. After reviewing related work in Section X, the paper concludes with a discussion of some ideas on the next steps in the development of capable domestic service robots.

II. Hardware Design

Dynamaid's hardware design focused on low weight, sleek appearance, and dexterousity. These are important features for a robot that interacts with people in daily life environments.

In particular, the low weight has safety advantages, because the robot requires only limited actuator power and thus is inherently safer than a heavy-weight robot. The total weight of our robot is only 20kg, an order of magnitude lower than other domestic service robots. The slim torso and the anthropomorphic arms strengthen the robot's pleasant appearance.

With its omnidirectional driving and human-like reaching capabilities, Dynamaid is able to perform a wide variety of mobile manipulation tasks. Its humanoid upper body supports natural interaction with human users.

A. Omnidirectional Drive

Dynamaid's base (see Fig. 2) consists of four individually steerable differential drives, which are attached to corners of an rectangular aluminum chassis with size 60×42cm. Each pair of wheels is steered by a Robotis Dynamixel RX-64 actuator and the individual wheels are driven by EX-106 actuators.

A microcontroller controls the wheel speed and the orientation of the differential drives at a rate of about 100Hz. The main computer, a small notebook, implements omnidirectional driving by setting targets for the linear velocities and orientations of the differential drives at a rate of 50Hz.

For navigation purposes, the base is equipped with a SICK S300 laser range finder. It provides distance measurements of up to 30m in an angular field-of-view of 270°. Two ultrasonic distance sensors cover the blind spot to the back of the robot.

Overall, the mobile base only weighs about 5kg. Its maximum payload is 20kg.

B. Anthropomorphic Upper Body

Dynamaid's upper body consists of two anthropomorphic arms, a movable head, and an actuated trunk. All joints are also driven by Dynamixel actuators. Each arm (see Fig. 3) has seven joints. We designed the arm size, joint configuration, and range of motion to resemble human reaching capabilities. Each arm is equipped with a 2 degree of freedom (DOF) gripper. Its maximum payload is 1kg.

From trunk to gripper an arm consists of a 3 DOF shoulder, an 1 DOF elbow, and a 3 DOF wrist joint. The shoulder pitch joint is driven by two EX-106 actuators in synchronous mode to reach a holding torque of 20Nm and a maximum rotational speed of 2.3rad/s. Single EX-106 servos actuate the shoulder roll, the shoulder yaw, and the elbow pitch joint. The wrist consists of RX-64 actuators (6.4Nm, 2rad/s) in yaw and pitch joint and a RX-28 servo (3.8Nm, 2.6rad/s) in the wrist roll joint. Both joints in the gripper are actuated by RX-28 servos.

The gripper contains four Sharp infrared (IR) distance sensors. With these sensors Dynamaid is able to directly measure the alignment of the gripper towards objects. They measure distance in the range 4cm to 30cm. One sensor is attached at the bottom of the wrist to measure objects like the table, for instance. Another sensor in the wrist perceives objects inside the hand. Finally, one sensor is attached at the tip of each finger.

In the trunk, Dynamaid is equipped with a Hokuyo URG-04LX laser range finder. The sensor is mounted on a RX-28 actuator to twist the sensor around its roll axis which is very useful to detect objects in the horizontal and in the vertical plane.

The trunk is additionally equipped with two joints. One trunk actuator can lift the entire upper body by 1m. This allows for object manipulation in different heights. In the lowest position, the trunk laser is only 4cm above the ground. Hence, Dynamaid can pick up objects from the floor. In the highest position, Dynamaid is about 180cm tall and can grab objects from 100cm high tables. The second actuator allows to twist the upper body by ±90°. This extends the working space of the arms and allows the robot to face persons with its upper body without moving the base.

The head of Dynamaid consists of a white human face mask, a directional microphone, a time-of-flight camera, and a stereo camera on a pan-tilt neck built from 2 Dynamixel RX-64 actuators. The stereo camera consists of two PointGrey Flea2-13S2C-C color cameras with a maximum resolution of 1280x960 pixels. A MESA SwissRanger SR4000 camera is

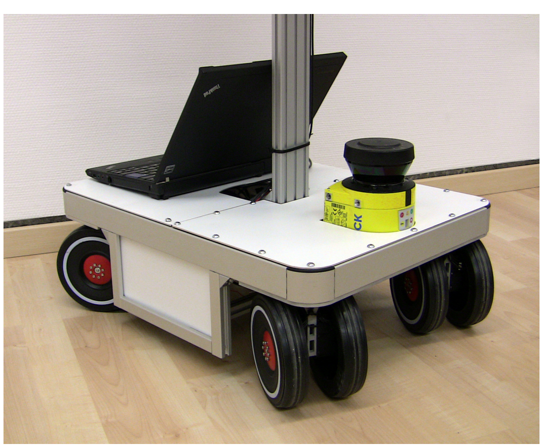

Fig. 2. Omnidirectional base with four individually steerable diff-drives.

Fig. 3. 7 DOF human-scale anthropomorphic arm with 2 DOF gripper.

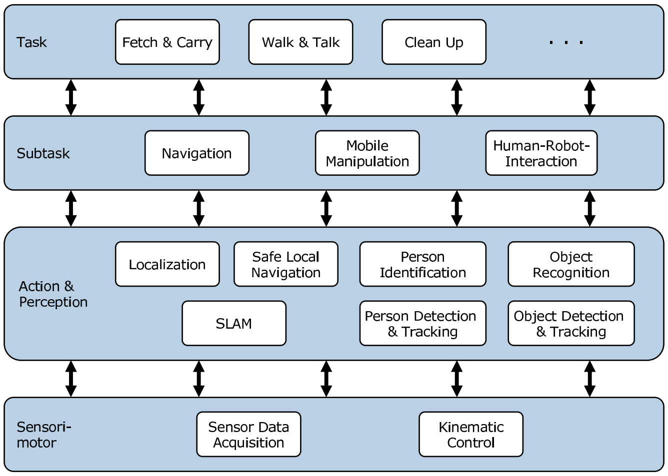

Fig. 4. Overview over the control modules within Dynamaid's behavior architecture.

located between the two stereo cameras. It measures distance to objects within a range of 10m.

Overall, Dynamaid currently has 35 joints, which can be accessed from the main computer via USB. The robot is powered by Kokam 5Ah Lithium polymer cells, which last for about 30min of operation. Further details on the hardware design of Dynamaid can be found in [1].

III. Behavior Control Architecture

Domestic service tasks require highly complex coordination of actuation and sensing. Thus, for successful system integration, a structured approach to behavior design is mandatory.

Dynamaid's autonomous behavior is generated in a modular multi-threaded control architecture. We employ the inter process communication infrastructure of the Player/Stage project [2]. The control modules are organized in four layers as shown in Fig. 4.

On the *sensorimotor layer*, data is acquired from the sensors and position targets are generated and sent to the actuating hardware components. The kinematic control module, for example, processes distance measurements of the IR sensors in the gripper and feeds back control commands for the omnidirectional drive and the actuators in torso and arm.

The *action-and-perception layer* contains modules for person and object perception, safe local navigation, localization, and mapping. These modules use sensorimotor skills to achieve reactive action and they process sensory information to perceive the state of the environment. E.g. the local navigation module perceives its close surrounding with the SICK S300 LRF to drive safely to target poses.

Modules on the *subtask layer* coordinate sensorimotor skills, reactive action, and environment perception to achieve higher-level actions like mobile manipulation, navigation, and human-robot-interaction. For example, the mobile manipulation module combines motion primitives for grasping and carrying of objects with safe omnidirectional driving and object detection.

Finally, at the *task layer* the subtasks are further combined to solve complex tasks that require navigation, mobile manipulation, and human-robot-interaction. One such task in the RoboCup@home competition is to fetch one specific object out of a collection of objects from a shelf. The object is selected by a human user who is not familiar with the robot's usage. Together, the subtask and the task layer form a hierarchical finite state machine.

Our modular architecture design reduces the complexity of high-level domestic service tasks by successive abstraction through the layers. Lower layer modules inform higher layer modules comprehensively and abstract about the current state of the system. Higher layer modules configure lower layer modules through abstract interfaces. Also, while lower layer modules need more frequent and precise execution timing, higher layer modules are executed at lower frequency and precision.

IV. Sensorimotor Skills

High movability is an important property of a domestic service robot. It must be able to maneuver close to obstacles and through narrow passages. To manipulate objects in a typical domestic environment, the robot needs the ability to reach objects on a wide range of heights, in large distances, and in flexible postures to avoid obstacles.

A. Control of the omnidirectional drive

We developed a control algorithm for Dynamaid's mobile base that enables the robot to drive omnidirectionally. Its driving velocity can be set to arbitrary combinations of linear and rotational velocities. The orientation of the four drives and the linear velocities of the eight wheels are controlled kinematically such that their instantaneous centers of rotation (ICRs) coincide with the ICR that results from the velocity commands for the center of the base.

The drives are mechanically restricted to a $270°$ orientation range. Thus, it is necessary to flip the orientation of a drive by $180°$, if it is close to its orientation limit.

The main computer sends the target orientations and linear velocities to the microcontroller that communicates with the Dynamixel actuators. The microcontroller in turn implements closed-loop control of the wheel velocities. It smoothly aligns the drives to their target orientations by rotating simultaneously with the yaw actuators and the wheels. If a drive deviates significantly from its target orientation, the base slows down quickly and the drive is realigned.

B. Control of the anthropomorphic arm

The arm is controlled using differential inverse kinematics to follow trajectories of either the 6 DOF end-effector pose or the 3 DOF end-effector position

$$\dot{\theta} \;=\; J^{\#}(\theta)\, \dot{x} \;-\; \alpha\, \left(I - J^{\#}(\theta) J(\theta)\right)\, \frac{dg(\theta)}{d\theta}, \qquad (1)$$

where θ are the joint angles, x is the end-effector state variable, J and $J^{\#}$ are the Jacobian of the arm's forward kinematics and its pseudoinverse, respectively, and α is a step size parameter. Redundancy is resolved using nullspace optimization [3] of the cost function $g(\theta)$ that favors convenient joint angles and penalizes angles close to the joint limits.

We implemented several motion primitives for grasping, carrying, and handing over of objects. These motion primitives are either open-loop motion sequences or use feedback like the distance to objects as measured by the IR sensors, e.g., to adjust the height of the gripper over surfaces or to close the gripper when an object is detected between the fingers.

V. Perception of Objects and Persons

Domestic service applications necessarily involve the interaction with objects and people. Dynamaid is equipped with a variety of sensors to perceive its environment. Its main sensors for object and person detection are the SICK S300 LRF, the Hokuyo URG-04LX LRF, and the stereo camera. The stereo camera is further used to recognize objects and people.

A. Object detection and localization

We primarily use the Hokuyo URG-04LX LRF for object detection and localization. As the laser is mounted on an actuated roll joint, its scan is not restricted to the horizontal plane.

In horizontal alignment, the laser is used to find objects for grasping. The laser range scan is first segmented based on jump distance. Segments with specific size and Cartesian width are considered as potential objects. By filtering detections at a preferred object position over successive scans, object are robustly tracked. In the vertical scan plane, the laser is very useful for detecting and estimating distance to and height of objects like tables.

We use both types of object perception for mobile manipulation. We demonstrated their successful usage in the *Fetch & Carry* task at the RoboCup@home competition.

B. Object recognition

The locations of the detected objects are mapped into the image plane (see Fig. 5a). In the rectangular regions of interest, both color histograms and SURF features [4] are extracted. The combined descriptor is compared to a repository of stored object descriptors. For each object class, multiple descriptors are recorded from different view points during training, in order to achieve a view-independent object recognition. If the extracted descriptor is similar to a stored descriptor, an object hypothesis is initialized in egocentric coordinates, as shown in Part b) of Fig. 5. This hypothesis is maintained using a multi-hypothesis tracker, which integrates object observations over time. When a recognition hypothesis is confirmed over several frames, the recognition hypothesis becomes confident and the robot can use this information, e.g., to grasp a specific object.

C. Person detection and tracking

To interact with human users a robot requires situational awareness of the persons in its surrounding. For this purpose, Dynamaid detects and keeps track of nearby persons.

We combine both LRFs on the base and in the torso to track people. The SICK S300 LRF on the base detects legs, while the Hokuyo URG-04LX LRF detects trunks of people. Detections from the two sensors are fused with a Kalman filter which estimates position and velocity of a person. It also accounts for the ego-motion of the robot. In this way, we can robustly track a person in a dynamic environment which we could demonstrate in the *Follow Me* task at the RoboCup@home competition.

Dynamaid keeps track of multiple persons in her surrounding with a multi-hypothesis-tracker. A hypothesis is initialized from detections in the trunk laser range finder. Both types of measurements from the laser on the base and in the trunk are used to update the hypotheses. For associating measurements to hypotheses we use the Hungarian method [5].

Not every detection from the lasers is recognized as a person. Dynamaid verifies that a track corresponds to a person by looking towards the tracks and trying to detect a face in the camera images with the Viola&Jones algorithm [6].

D. Person identification

For the *Who-is-Who* and the *Party-Bot* tests, Dynamaid must introduce itself to persons and recognize these persons later on. Using the VeriLook SDK, we implemented a face enrollment and identification system. In the enrollment phase, Dynamaid approaches detected persons and asks them to look into the camera. The extracted face descriptors are stored in a repository. If Dynamaid meets a person later, she compares the new descriptor to the stored ones, in order to determine the identity of the person.

VI. Navigation

Most domestic service tasks are not carried out at one specific location, but require the robot to safely navigate in its environment. For this purpose, it must be able to estimate its pose in a given map, to plan obstacle free paths in the map, and to drive safely along the path despite dynamic obstacles. Finally, the robot needs the ability to acquire a map in a previously unknown environment with its sensors.

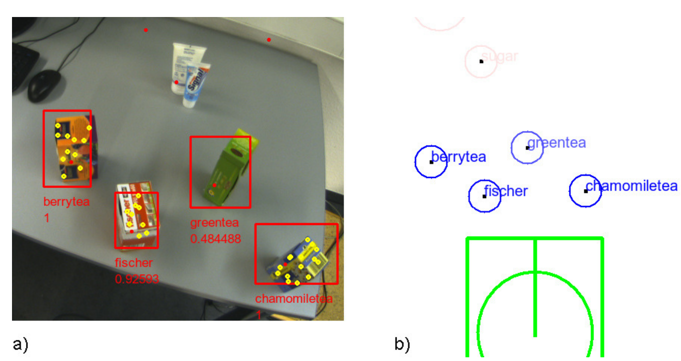

Fig. 5. Object Recognition: a) the camera image with rectangular object regions that are computed from LRF object detections. The image also shows extracted SURF features (yellow dots) and recognized object class. b) recognized objects are tracked in egocentric coordinates by a Kalman filter.

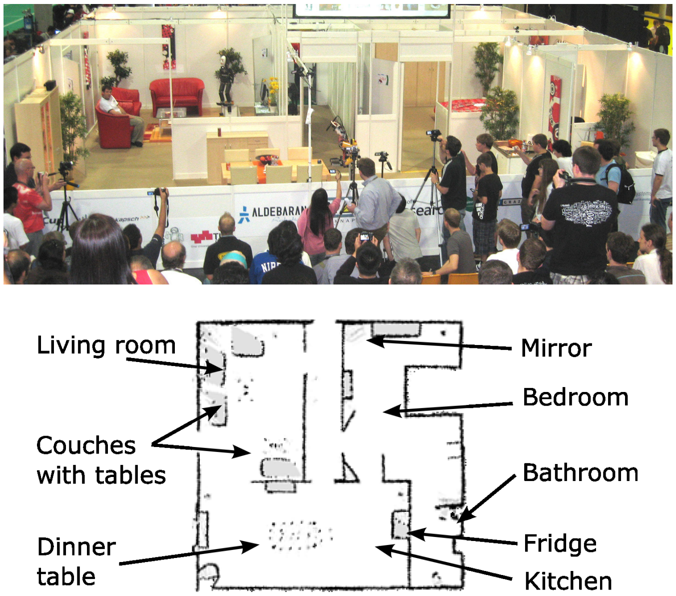

Fig. 6. Top: Arena of the 2009 RoboCup@Home competition in Graz. Bottom: Map of the arena generated with GMapping [8].

A. Simultaneous Localization and Mapping

To acquire maps of unknown environments, we apply a FastSLAM2 [7] approach to the Simultaneous Localization and Mapping (SLAM) problem. In this approach, the posterior over trajectory and map given motion commands and sensor readings is estimated with a set of weighted particles. By factorisation of the SLAM posterior, Rao-Blackwellization can be applied to the SLAM problem: The particles contain discrete trajectory estimates and individual map estimates in the form of occupancy grid maps. We apply the GMapping implementation [8] which is contained in the OpenSLAM open source repository. Fig. 6 shows the RoboCup@home arena at RoboCup 2009 in Graz and a generated map.

B. Localization

In typical indoor environments, large parts of the environment like walls and furniture are static. Thus, once the robot obtained a map of the environment through SLAM, it can use this map for localization.

We apply a variant of the adaptive Monte Carlo Localization [9] to estimate the robot's pose in a given occupancy grid map. The robot's main sensor for localization is the SICK S300 laser range finder. The particles are sampled from a probabilistic motion model which captures the noise in the execution of motion commands. When new laser sensor readings are available, the particles are weighted with the observation likelihood of the laser scan given the robot's pose. We use the end-point model for laser range scans, as it can be implemented efficiently through look-up tables and it is more robust than the ray-cast model to small changes in the environment.

C. Path planning

To navigate in its environment, the robot needs the ability to plan paths from its estimated pose in the map to target locations.

We apply A* search [10] to find short obstacle-avoiding paths in the grid map. As heuristics we use the Euclidean distance to the target location. The traversation cost of a cell is composed of the traveled Euclidean distance and an obstacle-density cost which is inversely proportional to the distance to the closest obstacle in the map. To be able to treat the robot as a point, we increase the obstacles in the map with the robot radius. By this, obstacle-free paths are found that trade-off shortness and distance to obstacles.

The resulting path is compressed to a list of waypoints. We generate waypoints when a specific travel distance to the previous waypoint has been reached or at locations on the path with high curvature.

D. Safe local navigation

The path planning module only considers obstacles which are represented in the map. To navigate in partially dynamic environments, we implemented a module for local path planning and obstacle avoidance.

From the sensor readings, we estimate a local occupancy grid map. Again, the obstacles are enlarged by the robot's shape. A path through the visible obstacle-free area is planned to the next waypoint by A* which also uses obstacle-density as a path cost component. The omnidirectional driving capability of our mobile base simplifies the execution of the planned path significantly.

VII. Mobile Manipulation

To robustly solve mobile manipulation tasks we integrate object detection, safe navigation, and motion primitives. Dynamaid can grasp objects, carry them, and hand them to human users.

To grasp an object from a specific location, Dynamaid first navigates roughly in front of the object through global navigation. Then, it uses vertical object detection to determine distance to and height of the horizontal surface to manipulate on. With its torso lifting actuator, it adjusts the height of the torso such that the trunk LRF measures objects shortly above the surface in the horizontal scan plane. It approaches the table as close as possible through safe local navigation. Next, it detects the object to manipulate in the horizontal plane. If necessary it aligns to the object in sidewards direction using safe local navigation again. Finally, it performs a motion primitive to grasp the object at the perceived location.

When Dynamaid hands-over an object to a human, the user can trigger the release of the object either by a speech command or by simply taking the object. As the arm actuators are back-drivable and support moderate compliance, the user can easily displace them by pulling the object. The actuators measure this displacement. The arm complies to the motion of the user. When the pulling persists, Dynamaid opens her

Fig. 7. Dynamaid delivers a cereal box during the *Supermarket* test at RoboCup 2009 in Graz.

gripper and releases the object. Fig. 7 shows how Dynamaid hands an object to a human user during RoboCup 2009.

VIII. Human-Robot Interaction

Dynamaid mainly communicates with humans through speech. For both speech synthesis and recognition we use the commercial system from Loquendo. To make communication with Dynamaid more intuitive, Dynamaid gazes at tracked people by using its pan-tilt neck.

Loquendo's speech recognition is speaker-independent and recognizes predefined grammars even in noisy environments.

The Loquendo text-to-speech system supports expressive cues to speak with natural and colorful intonation. It also supports modulation of pitch and speed, and special sounds like laughing and coughing. Qualitatively, the female synthesized speech is very human-like.

We implemented also several gestures that Dynamaid performs with her arms and her head, such as greeting people and pointing to objects. One advantage of using anthropomorphic robots is that the human users can use a human motion model to predict the robot motion. We utilize this, for example, by gazing in driving direction and by gazing at objects prior to grasping.

IX. System Evaluation

Benchmarking robotic systems is difficult. While videos of robot performances captured in ones own lab are frequently impressive; in recent years, robot competitions, such as the DARPA Grand and Urban Challenges and RoboCup, play an important role in assessing the performance of robot systems.

At such a competition, the robot has to perform tasks defined by the rules of the competition, in a given environment at a predetermined time. The simultaneous presence of multiple teams allows for a direct comparison of the robot systems by measuring objective performance criteria, and also by subjective judgment of the scientific and technical merit by a jury.

The international RoboCup competitions, best known for robot soccer, also include now the @Home league for domestic service robots. The rules of the league require fully autonomous robots to robustly navigate in a home environment, to interact with human users using speech and gestures, and to manipulate objects that are placed on the floor, in shelves, or on tables. The robots can show their capabilities in several predefined tests, such as following a person, fetching an object, or recognizing persons. In addition, there are open challenges and the final demonstration, where the teams can highlight the capabilities of their robots in self-defined tasks.

A. RoboCup German Open 2009

Our team NimbRo [11] participated for the first time in the @Home league at RoboCup German Open 2009 during Hannover Fair.

In Stage I, we used our communication robot Robotinho for the *Introduce* task. In this test, the robot has to introduce itself and the development team to the audience. It may interact with humans to demonstrate its human-robot-interaction skills. The team leaders of the other teams judge the performance of the robot on criteria like quality of human-robot-interaction, appearance, and robustness of mobility. Robotinho explained itself and Dynamaid and interacted with a human in a natural way. The jury awarded Robotinho the highest score of all robots in this test.

For the *Follow Me* test, we used Dynamaid. She was able to quickly follow an unknown human through the arena, outside into an unknown, dynamic, and cluttered environment, and back into the arena again. She also could be controlled by voice commands to stop, to move in some directions, and to start following the unknown person. Performance criteria in this test are human-robot-interaction, safe navigation, and robust person following. Dynamaid achieved the highest score at this test.

Dynamaid also accomplished the *Fetch & Carry* task very well. For this test, a human user asks Dynamaid to fetch an object from one out of five locations. The user is allowed to give a hint for the location through speech. Dynamaid delivered reliably the requested object and scored the highest score again for her human-robot-interaction and manipulation skills.

In Stage II, Dynamaid did the *Walk & Talk* task perfectly. A human showed her five places in the apartment that she could visit afterwards as requested by spoken commands. Shortly before the run, the apartment is modified to test the ability of the robots to navigate in unknown environments.

In the *Demo Challenge*, Dynamaid demonstrated her skills as a waitress: Multiple users could order different drinks that she fetched quickly and reliably from various places in the apartment.

In the final, Robotinho gave a tour through the apartment while Dynamaid fetched a drink for a guest. The score in the final is composed of the previous performance of the team in Stage I and Stage II and an evaluation score by independent researchers that judge scientific contribution, originality, usability, presentation, multi-modality, difficulty, success, and relevance. A video of the robots' performance is available at our web page[1]. Overall, the NimbRo@Home team reached the second place, only a few points behind b-it-bots [12].

B. RoboCup 2009

Some of Dynamaid's features, such as object recognition, face recognition, the second arm, and the movable trunk became operational for the RoboCup 2009 competition, which took place in July in Graz, Austria. Fig. 6 shows both of our Robots in the arena, which consisted of a living room, a kitchen, a bedroom, a bathroom, and an entrance corridor. 18 teams from 9 countries participated in this competition.

In the *Introduce* test, Robotinho explained itself and Dynamaid, while she cleaned-up an object from the table. Together, our robots reached the highest score in this test.

Dynamaid successfully performed the *Follow Me* and the *Who-is-Who* test. In *Who-is-Who* the robot must detect three persons, approach them, ask for their names, remember their faces, and recognize them again when they leave the apartment. Dynamaid detected one person and recognized this person among the three persons leaving. She reached the second highest score in this test. Both robots reached the second highest score in the *Open Challenge*, where Robotinho gave a home tour to a guest while Dynamaid delivered a drink.

In Stage II, Dynamaid performed the *Walk & Talk* test very well. In the *Supermarket* test, the robot must fetch three objects from a shelf on spoken command of a user. The robot must first explain its operation to the user. Dynamaid recognized all requested objects, fetched two of them from different levels, and handed them to the user. This yielded the highest score in the test.

Dynamaid also performed the *Partybot* test very well. She detected a person, asked for its name, went to the fridge, recognized the person when it ordered a drink, and delivered the drink.

Both robots were used in the *Demo Challenge*. The theme of the challenge was 'in the bar'. Robotinho offered snacks to the guests while Dynamaid detected persons, approached them, offered drinks, took the orders, fetched the drinks from the kitchen table, and delivered them to the guest. The jury awarded 90% of the reachable points for this performance.

After Stage II, our team had the second most points, almost on par with the leading team. In the final, Dynamaid detected persons and delivered drinks to them. Overall, our team reached the third place in the @Home competition. We won also the innovation award for "Innovative robot body design, empathic behaviors, and robot-robot cooperation".

[1] http://www.NimbRo.net/@Home

X. Related Work

An increasing number of research groups worldwide are working on complex robots for domestic service applications. For example, the Personal Robot One (PR1) [13] has been developed at Stanford University. The design couples a differential drive with torso rotation to approximate holonomic motion. The robot has two 7DOF arms for teleoperated manipulation. The authors discuss safety issues. Compared e.g. to a Puma-560 industrial robot, the risk of serious injury is reduced dramatically. The successor PR2 is currently developed by Willow Garage. It has four individually steerable wheels, similar to our robot.

The U.S. company Anybots [14] developed the robot Monty (170cm, 72kg), which has one fully articulated hand (driven by 18 motors) and one gripper, and balances on two wheels. The robot is supplied externally with compressed air. Video is available online, where the robot manipulates household objects by using teleoperation.

At Waseda University in Japan, the robot Twendy-One [15] is being developed. Twendy-One is 147cm high and has a weight of 111kg. It moves on an omnidirectional wheeled base and has two anthropomorphic arms with four-fingered hands. The head contains cameras, but is not expressive. Several videos captured in the lab are available, where the robot manipulates various objects, presumably teleoperated.

One impressive piece of engineering is the robot Rollin' Justin [16], developed at DLR, Germany. Justin is equipped with larger-than human compliantly controlled light weight arms and two four finger hands. The upper body is supported by a four-wheeled mobile platform with individually steerable wheels, similar to our design. While Justin is able to perform impressive demonstrations, e.g. at CeBit 2009, the robot does not yet seem to be capable of autonomous operation in a home environment, as required for RoboCup@Home. The DLR arms have also been used in the DESIRE project [17].

The Care-O-Bot 3 [18] is the latest version of the domestic service robots developed at Fraunhofer IPA. The robot is equipped with four individually steerable wheels, a 7 DOF industrial manipulator from Schunk, and a tray for interaction with persons. Objects are not directly passed from the robot to persons, but placed on the tray.

XI. Conclusion

The experiences made at RoboCup German Open and RoboCup 2009 in Graz clearly demonstrate our success in integrating robust navigation, mobile manipulation, and intuitive human-robot-interaction in our domestic service robot Dynamaid. In contrast to other systems [19, 12], which consist mainly of a differential drive and a small Katana manipulator, Dynamaid's omnidirectional base allows for flexible motion in the narrow passages found in home environments. The anthropomorphic design of its upper body and the torso lift actuator enables it to handle objects in a wide range of everyday household situations. Its anthropomorphic body scheme facilitates natural interaction with human users. In addition to robust navigation and object manipulation, Dynamaid's human-robot-interaction skills were also well received by the high-profile juries.

In contrast to the systems described in Section X, Dynamaid is light-weight, modular, inexpensive, easy to interface, and fully autonomous. To construct the robot, we relied on intelligent actuators that we used before to construct the humanoid soccer robots, which won the RoboCup 2007 and 2008 soccer tournaments [20].

In our modular control architecture, we implemented task execution in hierarchical finite state machines. The abstraction through the behavior layers reduces the complexity in the design of states and state transitions. By this, robust task execution can be achieved.

Dynamaid's navigation capabilities mainly rely on 2D environment representations perceived through 2D laser range finders. Localization in such maps works reliably when large parts of the environment remain static. Safe collision-free navigation is possible when obstacles can be measured in one of the scan planes of the LRFs.

Dynamaid demonstrated successful mobile manipulation in the RoboCup setting. Our approach to coordinate object perception, safe local navigation, and kinematic control yields high success rates. While a single gripper can handle objects in sizes from about 5 cm to 15 cm width, both arms are needed to manipulate larger objects.

For communication with users Dynamaid primarily utilizes speech. Dynamaid's dialogue system guides the conversation to achieve the task goal. Her humanoid upper body scheme helps the user to perceive the robot's attention. Gaze control strategies make the actions of the robot predictable for users.

In future work, we will implement planning on the task and subtask layers to achieve more flexible behavior and to relieve the behavior designer from foreseeing the course of actions. Also, the perception and representation of semantic knowledge is required for high-level planning. To improve navigation, we work on the integration of 3D perception with TOF-cameras and gaze strategies for obstacle avoidance. The representation of movable objects like doors and furniture will further improve the robustness of localization and mapping. For mobile manipulation in more unconstrained environments, for example, for grasping obstructed objects from shelves or for receiving objects from users, real-time motion planning techniques will be required.

In the current state, Dynamaid is not finished. We plan to equip Dynamaid with an expressive communication head, as demonstrated by Robotinho [21, 11]. This will make intuitive multimodal communication with humans easier.

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