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Dynamaid, an Anthropomorphic Robot for Research on Domestic Service Applications

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***Abstract*— Domestic tasks require three main skills from autonomous robots: robust navigation, object 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 manipulation, Dynamaid is equipped with an anthropomorphic arm and a gripper. For intuitive multimodal communication, the robot has a microphone, stereo cameras, and a movable head. It can perceive persons in its environment, recognize and synthesize speech.

We developed software for the tests of the RoboCup@Home competitions, where robots must autonomously perform useful tasks in a home environment. In April 2009, Dynamaid took part in the RoboCup German Open competition at the Hannover Messe industrial trade fair. Together with our communication robot Robotinho, she performed very well.

***Index Terms*— domestic service robotics, mobile manipulation, human-robot-interaction**

I. INTRODUCTION

When robots will leave industrial mass production to help with household chores, the requirements for robot platforms will change. While industrial production requires strength, precision, speed, and endurance, domestic service tasks require different capabilities from the robots. The three most important skills for an autonomous household robot are: robust navigation in indoor environments, object manipulation, and intuitive communication with the users.

Robust navigation requires 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 a dexterous arm and a gripper that can handle the payload of common household objects. Intuitive communication with the users requires the use of multiple modalities, such as speech, gestures, mimics, and body language. Most available domestic robot systems support only one or two of the above skills.

In this paper, we describe our new robot Dynamaid, which we develop for research on domestic service applications. We equipped Dynamaid with an omnidirectional drive for robust navigation, an anthropomorphic arm 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 autonomously solving the tasks of the RoboCup@Home competitions. These competitions foster research on domestic service applications. They require fully autonomous robots to navigate in a home environment, to interact with human users, and to manipulate objects.

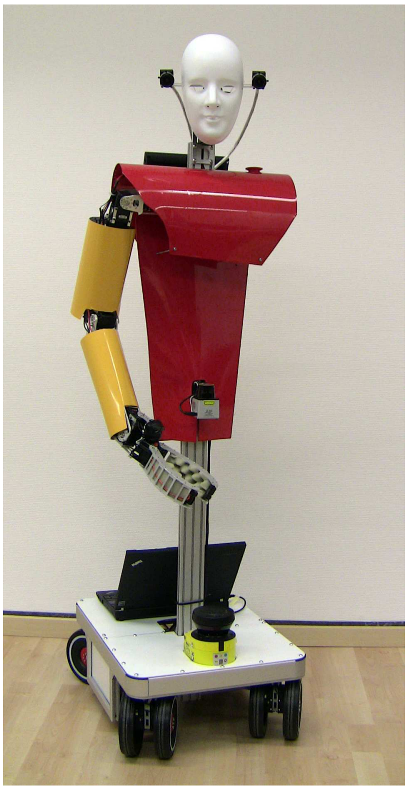

Fig. 1. The anthropomorphic service robot Dynamaid (in April 2009)

Together with our communication robot Robotinho, Dynamaid participated with great success at the RoboCup German Open, which took place at Hannover Messe in April 2009.

After describing the mechanical and electrical details of our robot in the next section, we cover the perception and behavior control software necessary for autonomous operation in Section III. In Section IV, we report the experiences made during the German Open competition. After reviewing related work in Section V, the paper concludes with a discussion of some ideas on the next steps in the development of capable domestic service robots.

II. HARDWARE DESIGN

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

In particular, the low weight is important for safety considerations, because the low weight requires only limited actuator power and thus Dynamaid is inherently safer than a heavyweight robot. As the robot only weighs about 12kg, a single person is able to carry the robot around. The slim torso and the anthropomorphic arm strengthen the robot's pleasant appearance. With its omnidirectional driving and human-like reaching capabilities, the robot can perform a wide variety of mobile manipulation tasks.

A. Omnidirectional Drive

Dynamaid's mobile base (see Fig. 2) consists of four individually steerable differential drives, which are attached to corners of an rectangular chassis with size 60×42cm. We constructed the chassis from light-weight aluminum sections. Each pair of wheels is connected to the chassis with a Robotis Dynamixel RX-64 actuator, which can measure the heading angle, and which is also used to control the steering angle. Both wheels of a wheel pair are driven individually by Dynamixel EX-106 actuators.

The Dynamixel intelligent actuators communicate bidirectioanlly via an RS-485 serial bus with an Atmel Atmega128 microcontroller at 1 Mbps baudrate. Via this bus, the control parameters of the actuators can be configured. The actuators report back position, speed, load, temperature, etc. The microcontroller controls the speed of the EX-106 actuators and smoothly aligns the differential drives to target orientations at a rate of about 100Hz. The main computer, a Lenovo X200 ThinkPad notebook, communicates over a RS-232 serial connection at 1Mbps with the microcontroller. It implements omnidirectional driving by controlling 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°. The standard deviation of a measurement is approx 8mm. Two ultrasonic distance sensors cover the blind spot in the back of the robot.

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

B. Anthropomorphic Upper Body

The anthropomorphic arm (see Fig. 3) has seven joints which are also driven by Dynamixel actuators. We designed its size, joint configuration, and range of motion to resemble human reaching capabilities. It is equipped with a 2 degree of freedom (DOF) gripper. Its maximum payload is 1kg.

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

All servos connect via a serial RS-485 bus to an Atmel Atmega128 microcontroller which forwards joint configurations like target joint angles, maximum torque, and target velocity from the main computer to the actuators. It also reports measured joint angles to the main computer.

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

The gripper contains four Sharp GP2D120XJ00F infrared (IR) 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 gripper.

The sensor readings are AD-converted by another Atmega128 microcontroller in the wrist. The microcontroller is connected as slave to the RS-485 network and forwards filtered measurements to the master microcontroller which communicates them to the main computer.

The head of Dynamaid consists of a white human face mask, a directional microphone, and a stereo camera on a pan-tilt neck built from 2 Dynamixel RX-64 actuators. The stereo camera consists of two PointGrey Flea2-13S2-C color cameras with a maximum resolution of 1280x960 pixels. We plan to replace the current head with a more expressive communication head like in our humanoid museum tour guide robot [1, 2].

Overall, Dynamaid currently has 24 joints, which can be accessed from the main computer via USB. The robot is powered by 5S2P Kokam 5Ah Lithium polymer cells, which last for about 60min of operation.

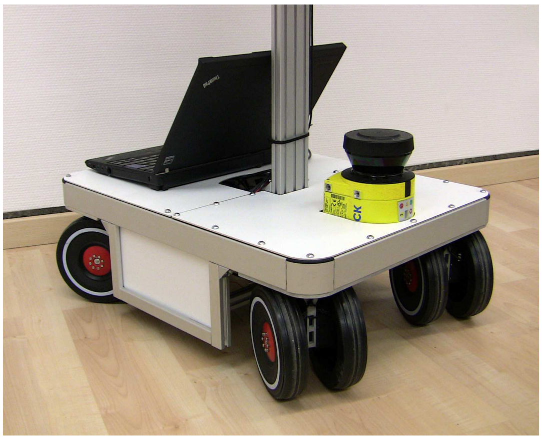

Fig. 2. Omnidirectional base with four individually steerable diff-drives.

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

III. BEHAVIOR CONTROL ARCHITECTURE

Domestic service tasks require highly complex coordination of actuation and sensing. To enable an autonomous robot to solve such a task, a structured approach 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 [3]. The control modules are organized in four layers.

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.

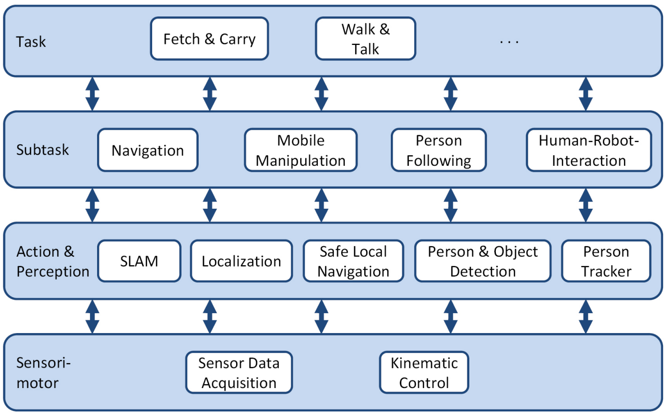

Fig. 4. Overview over the modules within Dynamaid's behavior architecture.

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 an object from a location in the environment after a human user gives a hint on the object location through spoken commands.

This 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 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 process at lower frequency and precision. Fig. 4 gives an overview of the architecture. In the following, we will detail the methods employed within Dynamaid's control architecture.

A. *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.

Dynamaid's mobile base is very maneuverable. It can drive omnidirectionally at arbitrary combinations of linear and rotational velocities within its speed limits.

Its 7 DOF anthropomorphic arm is controlled with redundant inverse kinematics [4]. With its human-like mechanical design it can reach objects in a wide range of heights at diverse arm postures. We implemented motion primitives, e.g. to grasp objects at arbitrary positions in the gripper's workspace.

1) 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 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 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 largely from its target orientation, the base slows down quickly and the drive is realigned.

2) 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

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

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 [5] 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.

B. 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 and the Hokuyo URG-04LX LRFs. The stereo camera is used to further improve detection and to recognize objects and people.

1) 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, the object is 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.

2) Person detection and tracking: 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 considers 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.

C. 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 to be able to acquire a map in a previously unknown environment with its sensors.

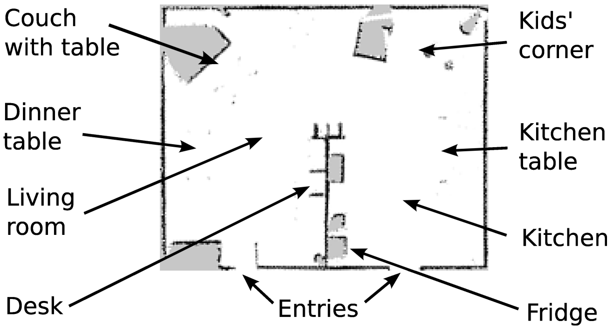

Fig. 5. Map of the RoboCup@home arena at German Open generated with GMapping [7].

1) SLAM: To acquire maps of unknown environments, we apply a FastSLAM2 [6] 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 closed-form map estimates in the form of occupancy grid maps. We apply the GMapping implementation [7] which is contained in the OpenSLAM open source repository. Fig. 5 shows a generated map of the RoboCup@home arena at GermanOpen.

2) 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 [8] 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.

3) 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 [9] 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 path is compressed to waypoints.

4) 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 for path cost. The omnidirectional driving capability of our mobile base simplifies the execution of the path significantly.

D. Mobile Manipulation

To solve mobile manipulation tasks we integrate object detection, safe navigation, and motion primitives sequentially. For example, 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 surface to manipulate on. It approaches the object 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. Then it performs a motion primitive to grasp the object.

E. Human-Robot Interaction

Dynamaid communicates with humans through speech and synthesized gestures like pointing and waving. For both speech synthesis and recognition we use the commercial system from Loquendo. To make communication 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 special sounds like laughing and coughing. Qualitatively, the female synthesized speech is very human-like.

IV. 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 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.

Our team NimbRo [2] 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 team to the audience. Robotinho explained itself and Dynamaid and interacted with a human in a natural way. The other team leaders awarded Robotinho the highest score.

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 could be controlled by voice commands to stop, to move in some directions, and to start following. Performance criteria in this test are human-robot-interaction, safe navigation, and robust person following. Dynamaid achieved the highest score at this competition.

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. She delivered reliably the requested object and gained 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 ordered drinks that she fetched quickly and reliably from various places in the apartment.

In the final, Robotinho gave a tour though the apartment while Dynamaid fetched a drink for a guest. In addition to the previous score in the competition, independent researchers judge for criteria like scientific contribution, usability, and presentation. A video of the final is available at our web page[1]. Overall, the NimbRo@Home team reached the second place, only a few points behind b-it-bots [10].

V. 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) [11] 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 will have four individually steerable wheels, similar to our robot.

The U.S. company Anybots [12] 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.

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

At Waseda University in Japan, the robot Twendy-One [13] (147cm, 111kg) is being developed. It moves on an omnidirectional wheeled base and has two anthropomorphic arms with four-fingered hands. The head contains cameras, but is not expressive. 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 [14], 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 [15].

The Care-O-Bot 3 [16] 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.

VI. CONCLUSION

The experiences made at RoboCup German Open clearly demonstrate that Dynamaid is suitable for research on domestic service applications. In contrast to other systems [17, 10], which consist mainly of a differential drive and a small Katana manipulator, Dynamaid has an omnidirectional base and is designed to handle everyday household objects, such as cups, glasses, or bottles.

In the current state, Dynamaid is not finished. In the next weeks, we plan to add a linear actuator that can move the upper body up and down. This will facilitate object manipulation on different heights, including the floor. We also are adding a second anthropomorphic arm, which will allow bimanual manipulation. Finally, we will equip Dynamaid with an expressive communication head, as demonstrated by Robotinho [1, 2]. This will make intuitive multimodal communication with humans easier. For the RoboCup 2009 competition, which will be held in July in Graz, we also continue to improve our perception and behavior control software in order to solve more tasks that require interaction with multiple persons, object and person recognition, and manipulation on the floor.

In contrast to the systems described in Section V, Dynamaid is light weight, modular, inexpensive, easy to interface, and fully autonomous. To construct the robot, we relied on intelligent actuators that we used for some time to construct the humanoid soccer robots, which won the RoboCup 2007 and 2008 soccer tournaments [18]. These actuators come in various sizes and are interfaced via a serial bus. In addition, we constructed sensor nodes for this bus.

While Dynamaid has been successfully used for research on domestic service applications, there remain many issues to be resolved before complex service robots will be available as a product. We think, the two main issues are perception and system integration. For acting in the world, the perception of the robot environment is essential. Current computer vision, speech recognition, and other sensor interpretation systems are far from human performance. The aspect of system integration should also not be underestimated, as the performance of the entire system is determined by the performance of the weakest component. System integration effort can be amortized over several research groups when a standard platform is used. The RoboCup Aibo and Nao leagues clearly demonstrated that using a common robot platform accelerates software development. Consequently, after some refinements, we plan to make Dynamaid available to other research groups.

ACKNOWLEDGMENT

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