

# Design and Control of a Domestic Service Robot

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**Abstract - Before service robots will be part of our daily lives, large-scale developments on both hardware and software are required. Nevertheless, service robots are currently only available to large research institutions that have the resources to develop one. The service robots that are available are usually far too expensive. Furthermore, the available service robots are not modular, and their designs are closed-source, hampering further development. Therefore, a modular service robot is required with standardized interfaces. Furthermore, it must be open hardware so that it can act as a reference implementation for future developments. This paper presents best practices in service robots and introduces a control design for a domestic service robot.**

**Keywords:** service robot design, sensorimotor control, hybrid control, anthropomorphic robot, cooperative manipulators.

## I. INTRODUCTION

Robots are expected to play an increasing role in society over the next number of years. They can, e.g., reduce the pressure on the home care system by assisting people with mobility impairments so that they can live independently at home for a longer time. Furthermore, robots will also increasingly work alongside people in industry. This illustrates the need for the development of versatile, reliable, robust and affordable robots.

As is mentioned in [1], it is expensive and time consuming to develop these robots. Nevertheless, many service robots have been developed over the past ten years. The development of the PR2 (based on the design in [2]) has concentrated on the design and implementation of a fully integrated development platform that is designed to be safe and capable in human environments. The long-term goal of the Care-O-bot project ([3],[4]) is to develop a mobile robot able to assist people in their homes and combines the technological aspects with a user-friendly design. The two-arm system in reference [5] is developed as a research platform to contribute to the manipulation skills of humanoid robots. Together with the platform introduced in [6], it also forms the mobile service robot Rollin' Justin. More humanoid research platforms are ARMAR-III [7], Dynamaid [8], TWENDY-ONE [9] and HoLLiE [10].

Similar to the computer industry, which quickly gained momentum after a standardized, open PC architecture was introduced, the development of service robots can greatly benefit from standardized interfaces that allow modular substitution of components. Modular components with standardized interfaces i) allow the use of hardware components for a specific task, ii) allow a robot to be assembled from components of multiple developers and iii) eases maintenance of the robots.

Modularity has been an important issue in a number of these designs. In [2] it is recognized that a modular approach makes it possible to add specialized hardware and end-effectors. The Care-O-bot 3 also has a modular setup [1] and has a modified, existing manipulator connected to an existing end-effector. Rollin' Justin ([5], [6]) also has a separately designed base, torso and arms. Similarly, ARMAR-III [7] and HoLLiE [10] have been designed as a mobile platform with a modular upper body. However, only the PR2 contains open interfaces to use different grippers, arms or sensors and the designs in [8] and [9] are in general less modular.

As is argued in [11], open-source software implementations of a standard means that the standard is more likely to be of high quality, since these implementations act as reference implementations, and that the standard is more likely to be adopted. Unfortunately, most of these robots are unique research platforms that are not available to other research institutions ([1], [6]). The platforms that are available such as the PR2 [2] and the Care-O-bot 3 [4] are too expensive for many research institutions. In the field of humanoid, walking robots, the importance of open-hardware has long been recognized, with the iCub [12], DARwIn-OP [13] and NimbRo-OP [14] as well-known examples. These robots, however, are not suitable as service robots.

The contribution of this paper is a contribution to the design and development of a domestic service robot with:

- Best practices in the service robot design, both for the upper body, base platforms and the manipulator
- Mechanical design requirements
- Description of the manipulator kinematics and contact dynamics
- Description of the environmental model
- Proposal of a controller for a cooperative manipulator

In the next section, the design principles of the base platforms are discussed, namely the design of base platform in Section IIa, its upper body and manipulators in Section IIb and IIc, respectively. Section III describes the mechanical design requirements. Section IV focuses on the manipulator kinematics and contact dynamics and Section V on the description of the environmental model. Finally, Section VI presents a proposal for a controller for cooperative manipulators.

## II. BEST PRACTICES IN SERVICE ROBOTS

Most of the robots introduced in Section I consist of a moving base, a torso with one or more degrees of freedom and one or two manipulators. Although many of the tasks that are currently demonstrated using service robots can be performed with only one manipulator, an anthropomorphic robot with two manipulators and a moving torso has the advantage that it can also perform bimanual manipulation. Therefore, focus will lie on these anthropomorphic robots. In this section, various possibilities for base platforms, torsos and manipulators are discussed.

### a) Base platforms

Base platforms for service robots can be divided in three categories: non-holonomic, semi-holonomic and fully holonomic platforms. A holonomic robot can drive in any direction without having to turn beforehand. Hence, both the number of controllable DoFs and the total number of DoFs equal 3 (two translations and one rotation). A non-holonomic robot has fewer controllable DoFs than the total number of DoFs. For example, a car is non-holonomic: it cannot drive sideways. A semi-holonomic platform is able to drive sideways. However, it first has to turn its wheels.

Non-holonomic robots have two differentially driven wheels and one or two passive caster wheels, e.g., the Pioneer P3-DX, or four or more differentially driven wheels, e.g., the Pioneer P3-AT. As is recognized, however, in [6], [7] and [8], this is not very beneficial for manipulation and maneuvering in tight spaces. The semi-omni directionality of the robots in [2], [6] and [8], is obtained using steering wheels, i.e., four individually driven steerable drives. Each drive has either one or two wheels, hence the total number of motors required for a platform is either eight or twelve. This large number of actuators is the main drawback of these platforms.

Therefore, a base using either Mecanum wheels or Omni wheels is an interesting alternative. These wheels have small rolls on their circumference, allowing the wheels to move freely in axial direction (in case of Omni-wheels) or under an angle (in case of Mecanum wheels). In [2], it was argued that

these fully holonomic platforms did not perform sufficiently robust in the presence of doorway thresholds, curbs and extension cords. Nevertheless, fully holonomic platforms are also successfully used in [9] and [10].

As is mentioned in [6], platforms with more than three wheels are statically over determined and hence require some form of suspension in order to maintain good ground contact. Wheel suspension is not specifically addressed in [8], [9] and [10]. Rollin' Justin [6] has an independent wheel suspension system. An example of adding compliance using a rotational degree of freedom between the front and rear axis can be found in, e.g., [15].

### b) Upper bodies

The successor of the design in [2] and the robot in [8] are equipped with telescopic spines. This results in a large vertical motion while keeping the center of gravity (CoG) in the middle of the robot. On the other hand, the robots in [5], [7], [9] and [10], have rotational DoFs. The upper bodies in [5], [9] and [10] each have one actuator per joint, whereas one of the DoFs in [5] is passive, i.e., the tilt of the chest is coupled to the base via tendons. The main advantage of having a pitch joint is that the robot can move its shoulders further forward, as is indicated in [5]. The absence of a pitch joint is a drawback because the robot needs to be positioned very accurately with respect to an object to allow a feasible grasping motion.

For large tilt motions, however, care has to be taken to prevent the robot from tipping over. In [6], this is solved by using a variable footprint, increasing the required number of actuators and the complexity and therewith the costs of the system. An alternative approach is presented in [10], where a stability measure is optimized in motion planning. However, the safety of the robot preferably does not depend on software.

### c) Manipulators

One of the key abilities of a service robot is the ability to transport objects. Hereto, the robots in Section I are all equipped with manipulators. These manipulators typically have up to seven degrees of freedom and most manipulators are either mechanically compliant or have torque sensors so that the controllers enable compliant control. The robots in [1] and [5] have industrial robot arms with seven DoFs and harmonic drives. The arms in [5] are equipped with torque sensors to allow compliant control. Both arms, however, are too large and too heavy for a dual arm domestic robot. The robot in [10] has arms with six DoFs using three Schunk Power balls, lacking the possibility to do compliant control. The arms of the robot in [8] are actuated by Dynamixel servo

actuators. Although these have a compliant mode in which they are back drivable, true impedance control is not possible. The robots in [2] and [9] also have seven DoFs but are mechanically compliant.

AMIGO's manipulators [16] have seven DoFs, of which six DoFs are driven by three differential joints. The use of differential joints results in a compact and anthropomorphic design [17]. All joints are equipped with absolute position sensors as well as torque sensors to allow impedance control. Nevertheless, this design is also not open hardware. Although recent developments show that variable-stiffness actuation is a promising research direction, it is concluded that a rigid arm with torque sensors leads to a simpler design of both hardware and controllers. To keep the compact design and anthropomorphic appearance, a design with differential joints similar to, e.g., [16] and [17], is desired. Compared to the current manipulators, a number of possible improvements is identified: i) reduce the backlash in the differential joints, ii) improve the absolute position sensors and iii) redesign the I/O to be compatible with the rest of the robot.

### III. MECHANICAL DESIGN REQUIREMENTS

With the previous experiences and the considerations mentioned in Section II, a base platform of a service robot should fulfill the following requirements:

- Minimize the number of required actuators for an omni directional platform of the fully holonomic base, i.e., it can have either omni wheels or Mecanum wheels. With respect to costs, it is furthermore desired to i) use off-the-shelf parts whenever possible and ii) design parts in such a way that production costs decrease with increasing production volumes.
- Since the robot is supposed to operate in domestic and care environments, it must be able to match human walking velocities up to  $v = 2.0 \text{ m/s} = 7.2 \text{ km/h}$ . To come to a timely stop in case of unexpected events, the robot must be able to accelerate to this velocity in 0.5 s, hence  $a = 4.0 \text{ m/s}^2$ .
- The width of the robot should be limited to 600 mm to easily get through door openings.
- The robot must be able to drive through wheelchair-accessible areas. This implies that a vertical edge up to 6 mm and a beveled edge with a slope up to 1:2 with a height up to 13 mm are allowed.
- To keep traction even at rigid, uneven surfaces, the wheels must be compliantly suspended.

The difference between omni wheels and Mecanum wheels is the angle on which the rollers are placed on the

wheel. Compared to omni wheels, Mecanum wheels have a number of advantages:

- With the same total width and wheel size, a Mecanum wheel platform has a wider track and a longer wheelbase (0.55 m) compared to an omni wheel platform (0.46 m), resulting in a more stable platform (see Figure 1).
- Together with a more favorable position of the motors this also results in more space for peripheral equipment.
- Finally, driving over doorway thresholds is smoother because the wheels roll along their circumference instead of the circumference of the small rollers.

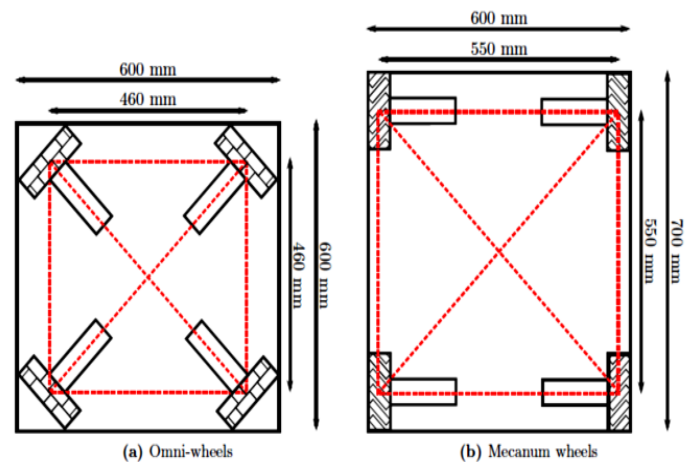


Figure 1: Schematic layout of an omni-wheel and an Mecanum wheel platform

Although some of the robots in Section I are equipped with a spring damper system to handle uneven floors, no specific attention has been paid to the resulting driving characteristics. Nevertheless, as is well-known in the automotive industry, suspension design has a great influence on, e.g., the camber and castor angles over the wheel travel, the roll center height and dive and squat properties.

Therefore, various suspension concepts have been considered, with one or both axles mounted to the chassis with a rotational DoF, crossed bars and an independent suspension. Of these concepts, the independent multi-link suspension was selected. The main advantage of this concept is that the wheels will always be perpendicular to the surface, i.e., when the robot is accelerating in any direction as well as when driving over obstacles. This prevents vibrations that are otherwise introduced. A second advantage is that the center of the base platform is not occupied by suspension parts.

#### IV. MANIPULATOR KINEMATICS AND CONTACT DYNAMICS

In this section, the relevant background information about manipulator modeling and the environment with which it interacts is presented. The kinematic and dynamic equations are introduced for a non-redundant serial manipulator in contact with a compliant environment. The manipulator possesses 6 independent degrees of freedom such that the 3 positions and 3 orientations can be specified for the end-effector, hence the robot arm is non-redundant.

The links of the manipulators are assumed to be rigid while the joints exhibit no flexibility. The end-effector position  $p_e \in \mathbb{R}^3$  and orientation represented by the rotation matrix  $R_e \in SO(3)$  of the manipulator are related to the joint variables,  $\theta \in \mathbb{R}^6$   $\theta$  via the forward kinematics map (i.e.  $p_e(\theta)$ ,  $R_e(\theta)$ ). A common way to derive this map is by using Denavit-Hartenberg convention. The end effector velocities are related to the joint velocities by the geometric Jacobian,

$$\dot{p}_e = J(\theta)\dot{\theta} \tag{1}$$

Where:  $\dot{p}_e = [p_e^T \omega_e^T]^T, p_e \in \mathbb{R}^3, \omega_e \in \mathbb{R}^3$

Are the translational and the angular velocities expressed w.r.t. the base frame, respectively. The translational and angular accelerations w.r.t. the base frame follow from (1) as,

$$\dot{\dot{p}}_e = \dot{J}(\theta)\dot{\theta} + J(\theta)\ddot{\theta} \tag{2}$$

Where:

$$\dot{\dot{p}}_e = [\dot{p}_e^T \dot{\omega}_e^T]^T.$$

It is common to use a suitable parameterization for the orientation of the end-effector with less parameters than the rotation matrix (which has 9 parameters) in order to reduce computational complexity for the implementation of the control algorithm and trajectory planning. A minimal parameterization of the three-dimensional rotation group  $SO(3)$  requires 3 parameters. Examples of such representations are Euler angles and exponential parameterization. A problem with minimal parameterizations is that they cannot be both global (in the sense of a 1-1 map between the parameters and the rotation matrix) and non-singular. Ad hoc solutions such as redefining the inertial frame or switching to a different parameterization can in principle deal with these singularities. Unit quaternions, a non-minimal parameterization, are selected to compute the orientation error, since they are computationally efficient and can properly represent a large range of orientation angles. Given the rotation matrix  $R_e$ , its four-parameter singularity-free representation is given by the following unit quaternion,

$$q_e = [\eta_e, \epsilon_e^T]^T \in \mathbb{S}^3 \tag{3}$$

With:

$$\eta_e = \cos \gamma_e, \epsilon_e = \beta_e \sin \gamma_e$$

Where:

$$\gamma_e \in \mathbb{R}, \beta_e \in \mathbb{S}^2.$$

Being the rotation angle and unit vector of an equivalent angle/axis representation of the rotation matrix satisfying the unit norm constraint

$$\eta_e^2 + \epsilon_e^T \epsilon_e = 1 \tag{4}$$

and

$$\eta_e \geq 0 \text{ when } \gamma_e \in [-\pi, \pi].$$

The time derivative of the unit quaternion  $q_e$  is related to the spatial angular velocity  $\omega_e$  by,

$$\dot{q}_e = [\dot{\eta}_e \dot{\epsilon}_e] = 1/2 T(q_e) \omega_e = 1/2 [-\epsilon_e^T E(\eta_e, \epsilon_e)] \omega_e = 1/2 [-\epsilon_e^T \eta_e I_3 - S(\epsilon_e)] \omega_e \tag{5}$$

Where  $S$  is a skew-symmetric matrix and the following relations

$$E T(\eta_e, \epsilon_e) E(\eta_e, \epsilon_e) = I_3 - \epsilon_e \epsilon_e^T \tag{6}$$

$$T T(\eta_e, \epsilon_e) T(\eta_e, \epsilon_e) = I_3 \tag{7}$$

$$T(\eta_e, \epsilon_e) T T(\eta_e, \epsilon_e) = I_4 - q_e q_e^T \tag{8}$$

Are satisfied. The relation between the rotation matrix and unit quaternion is given by the Rodrigues' formula,

$$R_e(\eta_e, \epsilon_e) = (\eta_e^2 - \epsilon_e^T \epsilon_e) I_3 + 2 \epsilon_e \epsilon_e^T + 2 \eta_e S(\epsilon_e) \tag{9}$$

Where:

$$R_e(\eta_e, \epsilon_e) = R_e(-\eta_e, -\epsilon_e)$$

Which follows from the fact that  $\mathbb{S}^3$  is a double cover of  $SO(3)$  (i.e. the map from quaternions to rotation matrices is two-to-one).

#### V. ENVIRONMENTAL MODEL

Consider the end-effector making contact with an elastic surface described by,

$$\varphi(p_e) = h \tag{10}$$

Where  $\varphi$  is an at least twice differentiable function in its domain of definition and  $h$  parameterizes the surface deflection (or deformation).

The surface is assumed to be sufficiently smooth and convex. Common examples of such surfaces are planar,

$$\varphi(pe) = n^T(pe - p_0) \tag{11}$$

Where  $pe = [pe, xpe, ype, z]^T, n \in \mathbb{R}^3, p_0 \in \mathbb{R}^3$

Are the Cartesian coordinates, normal to the plane and the offset of the plane from the origin and spherical,

$$\varphi(pe) = \|pe - p_0\| - r_0$$

Where  $p_0 \in \mathbb{R}^3, r_0 \in \mathbb{R}, r_0 > 0$

Represent the position of its center and radius. For a frictionless and compliant surface, the normal component of the contact force exerted by the end-effector on the surface is modeled as,

$$f_{e,n} = \begin{cases} -keh & \text{if } h \leq 0 \\ 0 & \text{if } h > 0 \end{cases} \tag{12}$$

Where  $ke$  characterizes the stiffness of the surface. This model is known in the literature as the Kelvin model. The complete contact force vector exerted by the end-effector on the surface is given by,

$$f_e = n(pe)f_{e,n} \text{ where } n(pe) = (\partial\varphi(pe)/\partial pe)^T \tag{13}$$

Where  $n(pe)$  is the normal direction of the surface. The effect of contact friction can also be included in the model by considering the tangential components of the contact force

$$f_e = n(pe)f_{e,n} + t(pe)f_{e,t} \tag{14}$$

Where  $t(pe)$  represent the tangential directions of the surface and  $f_{e,t}$  the friction force which depends on the magnitude of the normal force (i.e.  $|f_{e,n}|$ ) and velocity of the end-effector. For the case  $h \leq 0$ , the robot is in contact with the environment (i.e. contact motion phase) and the surface is assumed frictionless. The assumption on the absence of

contact friction is solely motivated by theoretical reasons and the effect of contact friction is left as a perturbation to the nominal closed-loop system.

### VI. CONTROLLER FOR COOPERATIVE MANIPULATION

Over the past decades, several control algorithms have been proposed for cooperative manipulators. The algorithms that can control both forces and motion can be divided into hybrid position/force control schemes and impedance/admittance control schemes. In the hybrid control schemes, the coordination space is decoupled into motion and force-controlled directions, using a predefined and fixed selection matrix. Unexpected contact in motion-controlled directions can lead to damage of the object and manipulators, since the force in these directions is not controlled. In the impedance control schemes the dynamic relation between the forces and motion of the system is taken into account. Using impedance control, the task can be executed without leading to contact instability in the absence of precise knowledge of the contact directions. However, to achieve a satisfactory level of position/force tracking performance, the precise knowledge of contact directions is still required.

A cascade controller for cooperative manipulation is introduced. The block diagram of this controller is shown in Figure 2. A motion controller is at the lowest level of this scheme. The inner motion control loop is added to improve the tracking performance. The reference for this motion control law is obtained from an impedance relationship driven by the internal force error. The desired trajectory for each manipulator is obtained from the kinematic constraints between the object and the respective manipulator. Finally, the desired object motion is obtained from the external force-based impedance controller.

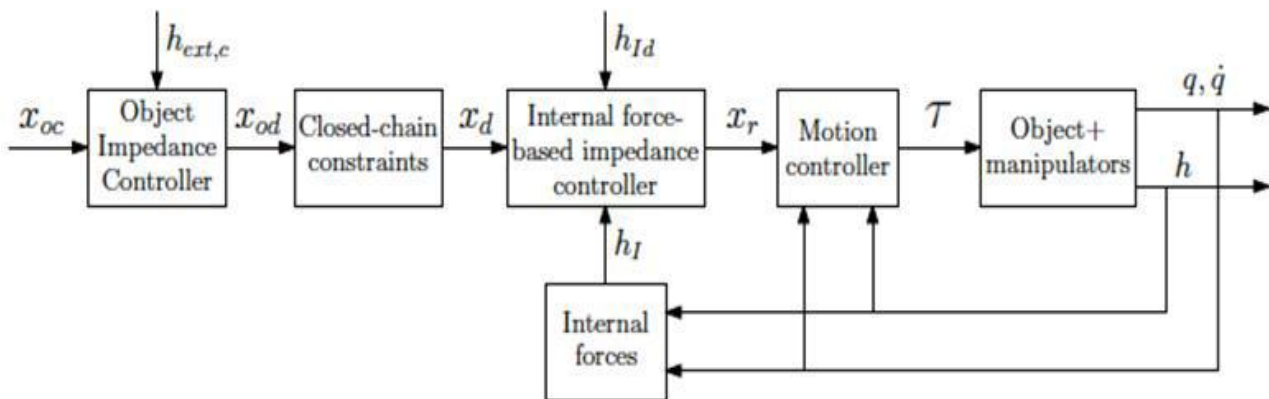


Figure 2: Control architecture of the cooperative manipulators

## VI. DISCUSSION AND CONCLUSION

For cooperative manipulation tasks, it is important to simultaneously control the motion of the system comprised of the manipulators and the object, the interaction forces between the object and the manipulators (internal forces) and the contact forces between the object and the environment (external forces).

The proposed hybrid control, consisting of the hybrid position/force control and impedance control, takes the previously described major contact problem issues into account. It is a control law suitable for implementation in unstructured environments.

A cascade control algorithm, based on the cooperative manipulation, is designed for the service robot control. With the proposed control algorithm for cooperative manipulation, the motion, internal and external forces of the object can be controlled. Using impedance relationships, a commanded object trajectory is converted into reference trajectories for the motion controllers of the manipulators such that the desired internal and contact forces can be achieved.

The next step towards the implementation in the rehabilitation would be to experimentally map the applied forces during the rehabilitation training and implement it in the proposed control algorithm.

## VII. FUTURE RECOMMENDATIONS

The desire to develop robots that can physically interact with humans in intuitive and biologically inspired ways has revealed a vast field of human-human physical interaction that has only begun to be studied. It may be advantageous to design robots that can be optimized to the functioning of the human nervous system. However, much work is to be done in human-human sensorimotor interactions before any general principles of cooperative sensorimotor control can be firmly established. As a first step, some areas of potentially fruitful investigation to reveal principles of sensorimotor cooperation in human-human interface that are directly relevant to the design of physical interfaces and control schemes for rehabilitation robots have been identified.

Specifically, new experimental paradigms should be developed that can address open questions of how motor redundancy, varying skill level, specific role assignment and reliance on haptic feedback play a role in the haptic cues and physical interactions between individuals. In particular, more attention in the specific areas of sensorimotor assistance and sensorimotor education could provide some guidance in the design of haptic interfaces and controllers for rehabilitation

robots. Possible motor tasks that could be used in such paradigms include but are not limited to: handshake, partner dance, sawing, carrying objects, leading an individual with visual impairment, and as a more direct clinical task, therapist-patient interactions during rehabilitation.

While several of these tasks have served as motivation for a number of human-human interface studies, there is a basic lack of understanding of the magnitude of forces used in these tasks. Additionally, how interaction forces contribute to task performance, or provide a channel for communicating information about motor performance, intent, and skill remains unknown. The identification of general principles of sensorimotor interaction between human partners may also be applicable to an alternative perspective of human-robot-interaction in rehabilitation. While the application of human-robot interaction in rehabilitation has traditionally focused on the robot-patient interaction, future work may also wish to consider human-robot interaction in rehabilitation from the perspective of a robot interacting with a therapist.

While the nature and challenges presented by the interaction between robot and therapist are likely to be different from those of robot-patient interactions, principles derived from the study of human-human interaction may serve to inform such interactions as well. Overall, the identification of guiding principles that drive human-human sensorimotor interactions and service robot design have the potential to further the design, control and use of rehabilitation robots that can physically interact with humans in intuitive and biologically inspired ways, thereby enhancing rehabilitation outcomes.

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