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The ACROBOTER Platform – Part 1: Conceptual Design and Dynamics Modeling Aspects

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Abstract. This paper presents the conceptual design and the dynamics modeling aspects of a pendulum-like under–actuated service robot platform ACROBOTER. The robot is designed to operate in indoor environments and perform pick and place tasks as well as carry other service robots with lower mobility. The ACROBOTER platform extends the workspace of these robots to the whole cubic volume of the indoor environment by utilizing the ceiling for planar movements. The cable suspended platform has a complex structure the dynamics of which is difficult to be modeled by using conventional robotic approaches. Instead, in this paper natural (Cartesian) coordinates are proposed to describe the configuration of the robot which leads to a dynamical model in the form of differential algebraic equations. The evolution of the ACROBOTER concepts is described in detail with a particular attention on the under–actuation and redundancy of the system. The influence of these properties and the applied differential algebraic model on the controller design is discussed.

1 Introduction

Obstacle avoidance is an important problem in service and mobile robotics. Robots operating in indoor environments have to overcome various static obstacles on the floor, e.g., chairs, tables, doorsteps and even the edges of carpets in a room. Thus floor based domestic robots need to have strategies to detect and avoid these randomly placed objects.

A new direction in the development of indoor service robots is the use of robotic structures that can move on the walls and/or on the ceiling of a room. An advantage

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of this strategy is that walls and rather the ceiling are almost obstacle free enabling robots to move freely and quickly in any direction. An application which addresses the need for a robot to climb on the walls and crawl on the ceiling inside a building is the MATS robot [1]. Another examples include the mobile robot platform described in [7] and the FLORA walking assisting system developed by FATEC Corporation [5]. Both of them are based on a ceiling absorbed mobile cart utilizing permanent magnets to keep and move the cart on the ceiling. The system [7] has a working unit that is positioned by three parallel telescopic arms. The FLORA robot has a specially designed cable suspended sit harness that can be used to compensate for the body weight of elderly or physically impaired people during walking. These platform concepts solve the problem of avoiding obstacles on the floor, while they are able to roam over almost the whole inner space of a room, and compared to gantry cranes, they enable the use of co-operating multiple units.

Similary, the ACROBOTER service robot is a ceiling based platform. Figures 1 and 4 present that the Climbing Unit (CU) can move in the plane of the suspended ceiling equipped with anchor points. In this first concept the CU is a planar robotic arm, which swaps between the anchor points and provides the crawling motion of the suspension of the robot. The windable suspending cable holds the Swinging Unit (SU) to which the carried objects can be connected. The system has a pendulum like structure, but compared to the above described systems [5, 7], here, the positioning of the payload is controlled by the actuators (fluid mass flow generators) of the SU. The proposed concept combine the planar stepping motion of the arm and the thrusted-hoisted pendulum-like motion of the working unit in 3D relative to the arm.

A design of a tethered aerial robot with a swinging actuator is presented in [6]. In this concept the weight of the robot is carried by a tether and the thrusting forces are generated by two fans with parallel axes. The main task of the robot is to carry a camera (and/or tiny robotic agents) used in rescue operations above unstructured

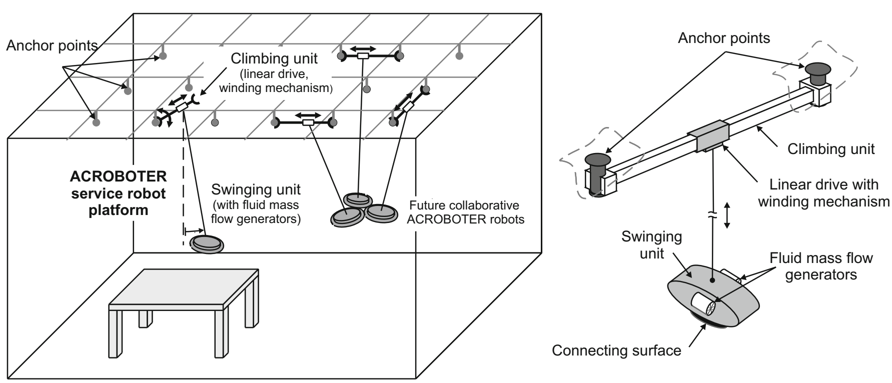

Fig. 1 The ACROBOTER concept: pendulum-like indoor service robot platform (left), main functional components of the system (right)

environments (e.g. at earthquake sites). Despite of the conceptual similarities to tethered aerial systems the different application scenarios of ACROBOTER requires a completely different design. The ACROBOTER platform ensures higher payload capability than aerial robots which may results in high inertial forces and nonlinear oscillations of the payload. In addition the pendulum like behavior of the system may also be utilized to provide better maneuverability and larger workspace in case of proper motion planning of the climbing unit.

2 Conceptual Design

The main task of ACROBOTER is to carry objects in the 3D space of inner environments. This can be accomplished in a set-point manner or the task may require the tracking of some desired trajectories. Hence, the swinging unit (see Fig. 1) needs to be fully actuated and controlled in the 3D environment. The CU has to move the suspension point of the swinging unit smoothly in the plane of the ceiling, while the actuators of the SU have to provide the desired orientation of the unit and its position relative to the CU.

In case of ACROBOTER the ceiling based traction unit, i.e. the climbing unit, is a planar RRT robot. The redundancy of this robot enables smooth planar movements when the CU has to swap between different anchor points (see left in Fig. 4). Different solutions like [5, 7] that provide the smooth movement of the suspension can also be considered.

The present chapter focuses on the design aspects of the swinging unit. The first prototype of the SU is presented in Fig. 2. In this concept two large diameter ducted fans are used to provide the desired nutation of the unit, while three windable orienting cables are used to control the roll and pitch of the platform. Ducted fans are

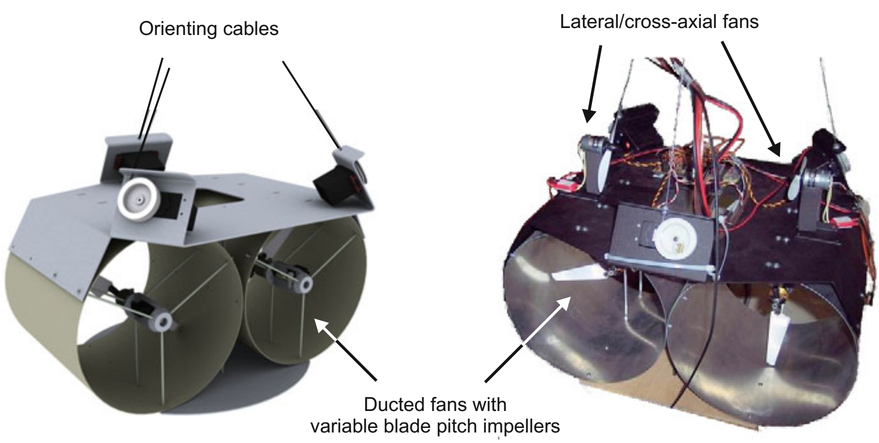

Fig. 2 First prototype of ACROBOTER: CAD design (left), built prototype with complementary lateral/cross-axial fans (right)

lightweight solution for on board thrust generation. The magnitude of the generated thrust is, however, proportional to the diameter of the fans which increases the size of the device when heavy payloads need to be nutated. The moment generated by the two parallel axis fans controls the yaw angle. In addition, the applied ducted fans have variable blade pitch impellers that can adjust the magnitude of the thrust forces or even they can quickly be reversed. This solution can provide large thrust forces, but the maneuverability of the concept is limited. The two ducted fans with parallel axes can only provide a thrust force paralell to the axes of the fans and a resultant moment acting upon the suspended payload as independent control inputs. Thus, the number of actuators is lower than the degrees of freedom of the suspended payload. To resolve the underactuation of the concept a pair of lateral/cross-axial fans were attached to the top of the first prototype of the SU (see right in Fig. 2).

The recognition of the under actuated character of the first design result in a new concept, which was also motivated by the need for decreasing the vertical dimension of the unit. The CAD models of the new concept are shown in Fig. 3 and the corresponding second prototype is depicted at right in Fig. 4. In this concept six identical ducted fans are used as thrusters that are placed around the circumference of a disk. The advantage of this solution is that the swinging unit can be fully actuated by using same ducted fan modules each providing a one-directional thrust force. The price that has to be paid is the lower resultant thrust that the smaller fans can provide. Therefore, developing the second prototype it was assumed that the SU will not provide large nutation for the carried objects. Instead, the fans will more effectively stabilize the motion of the unit around a desired trajectory. The gross motion is generated by the CU while the SU continuously compensates for the tracking errors.

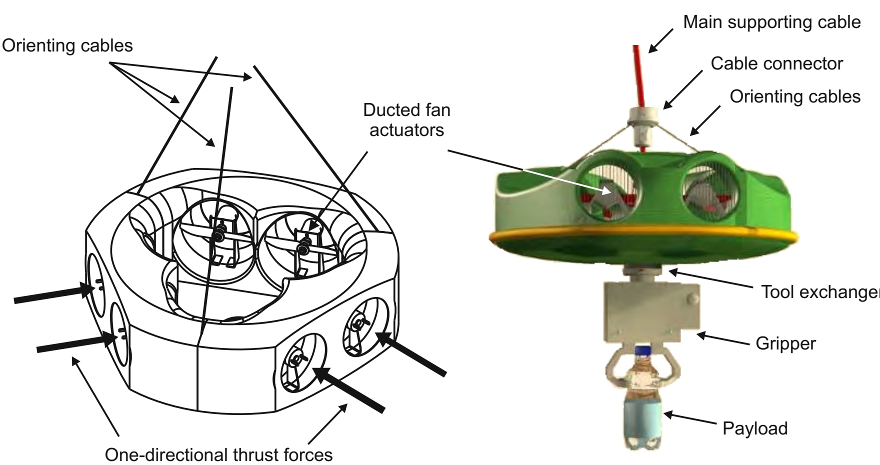

Fig. 3 Second prototype of ACROBOTER with six equally sized one-directional ducted fan actuators

3 Dynamics Modeling

The whole system prototype of ACROBOTER is presented in Fig. 4. This figure shows that the climbing unit is an RRT robot which has 3 degrees-of-freedom, when its upper (anchor) arm is attached to an anchor point. In this respect the CU can be described by conventional robotic approaches using the minimum set of descriptor coordinated, i.e. the generalized coordinates associated with the serial arm structure. The lower (rotation) arm of the CU is a linear axis that carries the winding mechanism hoisting the SU. Thus, including the winding mechanism, the climbing unit has 4DoFs. The main suspending cable and the orienting cables of the SU are connected by the cable connector (CC), which is a relatively small sized component and therefore can be modeled as a point mass with additional 3 DoFs. Then, considering the spatial 6DoFs of the SU, the system has 12DoFs in total, which requires the same number of generalized coordinates to describe its configuration.

Considering the completely different joint structure and actuation of the CU and the SU, the two systems were modeled independently from each other. The CU and the SU have separate motion controllers that are synchronized by the global motion controller of the system. The kinematic description of the CU follows the conventional robotic description and therefore not described here. The SU and the CC forms a cable suspended structure with a closed kinematic chain, where the ducted fan actuators cannot be associated with the real and/or virtual "joints" of the robotic structure. Thus, in case of the kinematic description of the SU the choice of coordinates has a key importance in obtaining a still complex but computationally affordable dynamical model.

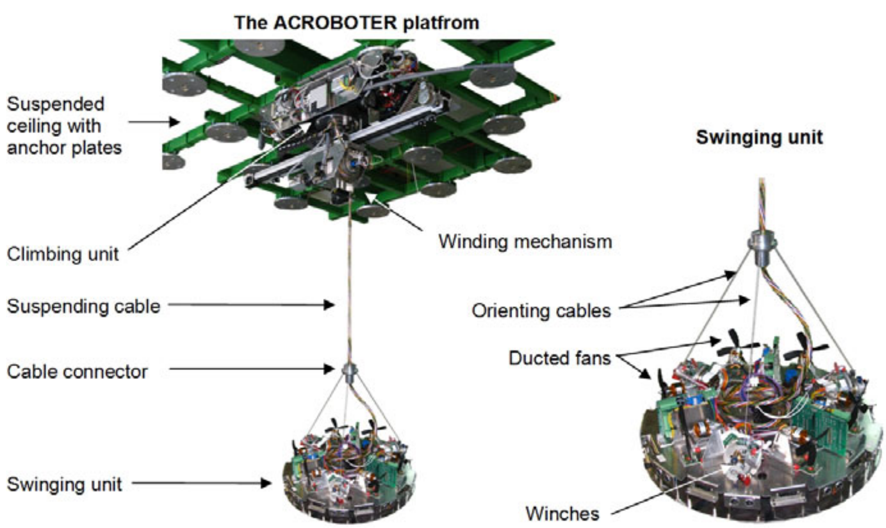

Fig. 4 The ACROBOTER service robot platform

An efficient parameterization of the affine transformation between the global (world) and the local (body) coordinate system of the SU is the use of natural coordinates originally introduced by [2]. This formalism uses a non-minimum set of specially chosen descriptor coordinates for the kinematic description of multibody systems including robotic structures, and the corresponding dynamics modeling is based on the Lagrangian equations of the first kind. This leads to the equations of motion in the well-known set of differential-algebraic equations of index 3

$$\mathbf{M}\ddot{\mathbf{q}} + \boldsymbol{\Phi}_{\mathbf{q}}^{\mathrm{T}}(\mathbf{q})\boldsymbol{\lambda} = \mathbf{Q}_g + \mathbf{H}(\mathbf{q})\mathbf{u}\,, \tag{1}$$

$$\boldsymbol{\phi}(\mathbf{q}) = \mathbf{0}\,, \tag{2}$$

where $\mathbf{q}$ denotes a redundant set of coordinates associated with the CC and the SU. The position of the CC is given by its Cartesian coordinates, while the pose of the SU is described by the coordinates of the co-planar points identified by the outlets of the winches and a unit vector which is perpendicular to the base of the SU. According to [2], the selection of these descriptor coordinates results in a constant mass matrix. The mass matrix $\mathbf{M}$, here, is a block diagonal matrix containing the mass matrices of the CC and SU, respectively. In eq. (1) the matrix $\boldsymbol{\Phi}_{\mathbf{q}} = \partial\boldsymbol{\phi}/\partial\mathbf{q}$ is the constraint Jacobian, $\boldsymbol{\lambda}$ is the vector of Lagrangian multipliers , $\mathbf{Q}_g$ is the constant generalized gravity force and $\mathbf{H}$ is the transmission matrix corresponding to the input vector $\mathbf{u}$. Note that in case of ACROBOTER the constraint equations (2) stand for the squared distances of the basic points (selected as cable outlets of the winches), and the perpendicularity and length of the unit vector the coordinates of which are also used as descriptor coordinates. Consequently, the constraint Jacobian is a linear function of the descriptor coordinates. Although, the number of coordinates are relatively high (15 in case of the model of the SU and the CC), the properties and the special structure of the resulting equations of motion make it possible to derive a real-time dynamic model of ACROBOTER.

Various methods exist for the solution of the equations of motion (1, 2). Simulation techniques involve the classical method of Lagrangian multipliers with Baumgarte stabilization [2, 8], and the projection method [3] which transforms the original set of differential algebraic equations (DAE) of motion to ordinary differential equations (ODE). Another possibility is to substitute the algebraic equations with singularly perturbed differential equations and use available stiff ODE solvers. The direct solution of equations (1) and (2) is possible by the index-reduction of the DAE problem which leads to the full descriptor form of index 1

$$\dot{\mathbf{q}} = \mathbf{p} \tag{3}$$

$$\dot{\mathbf{p}} = \mathbf{a} \tag{4}$$

$$\begin{bmatrix} \mathbf{M} & \boldsymbol{\Phi}_{\mathbf{q}}^{\mathrm{T}} \\ \boldsymbol{\Phi}_{\mathbf{q}} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{a} \\ \boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} \mathbf{Q}_g + \mathbf{H}(\mathbf{q})\mathbf{u} \\ -\dot{\boldsymbol{\Phi}}_{\mathbf{q}}(\mathbf{q},\mathbf{p})\mathbf{p} \end{bmatrix} \tag{5}$$

$$\boldsymbol{\phi}(\mathbf{q}) = \mathbf{0}\,. \tag{6}$$

The system of equations (4–6) can numerically be solved by backward difference methods (like the Backward-Euler method) via applying the Newton-Raphson iteration scheme to the resulting system of implicit algebraic equations.

4 Control Aspects

Based on the kinematic structure of ACROBOTER described in Section 3 it can be seen that the CU is a redundant manipulator, and moreover the base coordinate system of this arm is changing during swapping between the anchor points. This is an important issue in the control design of the climbing unit. Since the main suspending cable and the orienting cables can equally move the SU in the vertical direction the cable suspension system has a redundant character too. By assuming that the CU regulates the motion of the upper end of the main cable perfectly, the motion of this suspension point can be seen as a constraint on the independent dynamic model of the SU. This way the system formed by the SU and the CC has 9DoFs controlled by 7 actuators only. These include the 4 cable winches and a fictitious compound actuator that provides the two components of the resultant force and the resultant moment generated by the ducted fans. Thus the system is under–actuated, which means that two coordinates out of nine cannot be prescribed arbitrarily because they depend on the internal dynamics of the system. For example, consider that the SU have to move horizontally and the the elevation of the CC above the SU is prescribed. Then the motion of the CC parallel to the base of the SU cannot be actuated. Existing under–actuated robot control techniques (like [9]) are available for the class of systems where the equations of motions without control inputs can easily be identified, which is often the case for serial manipulators. When the control inputs are coupled by a transmission matrix the equation that describes the internal dynamics of the system can be achieved by projecting the equation of motion into the null-space of this matrix. Then, separating the coordinates into controlled and uncontrolled ones, the projected equation can be solved for the uncontrolled coordinates. These calculated coordinates can be seen as prescribed (uncontrolled) coordinates, which enables the generalization of the computed torque control method to under actuated robotic systems [4] modeled by minimum set of generalized coordinates. The computed torque control of ACROBOTER is based on the direct discretization of the differential algebraic equations of motion, which method is described in detail in Part 2 of the present work.

5 Conclusions

The main idea of a novel locomotion technology was presented in this paper and the design concepts of the cable suspended ACROBOTER platform were discussed. The main differences between the presented concepts are their vertical dimension and their maneuverability. Independently of the selected second prototype of the swinging unit it was concluded that the ACROBOTER has a complex spatial structure and it is advantageous to derive its equation of motion in terms of a redundant set of descriptor coordinates. The applied DAE model enables the efficient simulation of the model, while the use of the selected natural coordinates make it straightforward to calculate the forward/inverse kinematics of the system. The actuation scheme of the ACROBOTER robot were also discussed with a view on the possible realization of a computed torque controller.

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