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Development of the Acroboter Service Robot Platform

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Abstract The domestic robot platform Acroboter exploits a novel concept of ceiling based locomotion. The robot platform is designed to perform pick and place tasks as well as carry other service robots with lower mobility. The crane-like Acroboter platform extends the workspace of these robots to the whole cubic volume of the indoor environment by utilizing the almost obstacle free ceiling. We summarize the evolution of the structure of the robot, the dynamic modelling concept and the control strategy which are the results of concurrent engineering.

1 Introduction

Service robot manufacturing is an exponentially growing area. The service robots are mainly ground based and use wheels, tracked locomotion system or sometimes legs. A common problem of the ground based concepts is related to the randomly placed obstacles on the floor which are typical in everyday indoor environment, like tables and chairs, edges of carpets and children's toys. On the other hand, ground based robots share the same workspace that humans use and cannot extend, when a special task would require this, like in case of reaching the top of a shelf. Furthermore, they waste valuable cubic volume from humans' workspace. In order to solve the above-described difficulties, it is straightforward to use flying robots which utilize the full cubic volume of the environment instead of moving on the floor. However highly developed these flying applications

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like quadrocopters are, their application for domestic purposes encounters crucial problems. The energy consumption of flying vehicles is typically high and the power that can be provided by batteries enables only short time operation. Furthermore, the loading capacity of flying drones are typically low. The novel concept of the crane-like robot called Acroboter (Stepan et al., 2009) combines the positive features of flying robots and the energy efficiency and loadability of ground based mobile platforms. The Acroboter platform has been developed within the European Union 6th Framework Project (IST-2006-045530) coordinated by the Department of Applied Mechanics, Budapest University of Technology and Economics.

The subsequent sections detail the design issues and prototype evolution of the Acroboter platform as well as the mechanical modelling approach and control aspects.

2 Concept of the structural design

There exist a few similar ceiling based, crane-like robot concepts, like the Flora service robot (Sato et al., 2004), which utilizes permanent magnets to keep and move its mobile cart on the ceiling. A tethered aerial robot presented in (McKerrow and Ratner, 2007), of which the working unit is suspended on a single cable and equipped with two ducted fan actuators. A similar but simplified concept is the Winch-Bot that is presented in (Cunningham and Asada, Kobe, Japan, May 12-17, 2009.). Here the cable winch is the only actuator on the robot, which can perform pick-and-place tasks. In the technical report (Dorigo and et al., 2011) a parallel, distributed robotic system is introduced called Swarmanoid. The system has a few different type of units out of which there is one that can attach itself into the ceiling by a suspending cable and it can maneuver by using ducted fan actuators.

Similarly to the above-mentioned robotic systems, Acroboter can move on the almost obstacle free ceiling of a room, while transport the payload or a working unit similarly to gantry cranes, while it utilizes the pendulum-like motion efficiently (see sketch in Fig. 1 left).

A grid of anchor points (AP) is equipped on the ceiling. A climber unit (CU) moves from one to another anchor point by grasping two anchors at once or rotating around only one. The CU, which is a planar RRT robot, provides the main horizontal motion of the swinging unit (SU), which is the main working unit of Acroboter (see Fig. 1 right). The fine horizontal positioning of the final SU is performed by three pairs of ducted fan actuators (DF). The SU is equipped with a system of suspending and orienting cables. The main suspension cable (MC) is responsible for the elevation of the SU while the secondary cables (SC) of variable length are used for the precise stabilization of the orientation. The MC provides information signal and power transmission, too, although wireless communication between the main units is also implemented. The cable connector (CC) connects the main and secondary cables. The SU carries the end-effector of the robot which can be for example a grasper, but it is also possible to interchange the grasper unit to other machines, such as a vacuum cleaner, with the help of the mechanical and electrical interface, which plays the role of a tool-changer situated at the bottom of the SU.

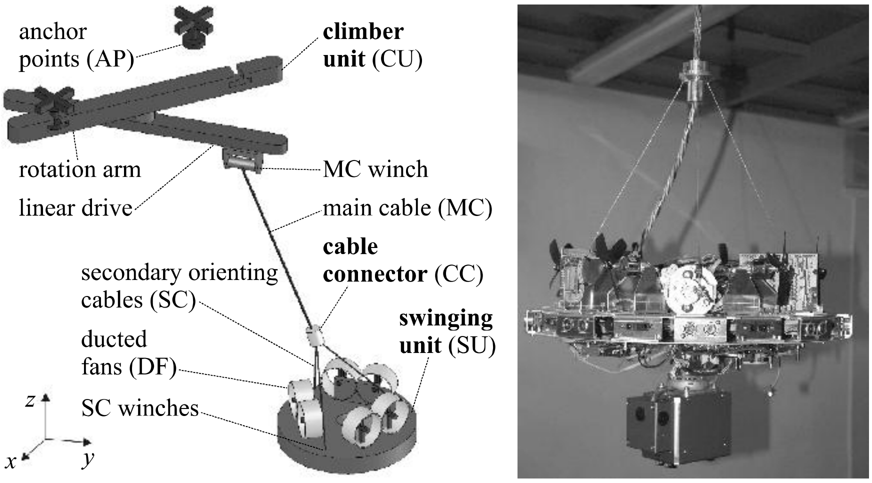

Figure 1. Sketch of the Acroboter (left), swinging unit prototype (right)

3 Dynamic modelling approach

In the classical modelling approaches of robots, the coordinates that describe the configuration of the model belong to the kinematic pairs involved. If the number of coordinates equals to the DoF then these joint coordinates are called *minimum set of generalized coordinates*. This approach is effective when open kinematic chains are modelled. When the dynamic modelling came into view, it was realized that Acroboter forms a complex multibody system, where the minimum set of coordinates is not effective as explained in the literature, e.g. (de Jalón and Bayo, 1994). The windable cables, the CC and the SU together form a parallel kinematic structure, which also makes it very hard to use minimum number of coordinates. This problem can be resolved by means of *non-minimum set of generalized coordinates*.

Out of the many possibilities we chose the so-called *natural coordinates*, which make real-time simulation possible and reduces computational costs even in case of highly complex multibody systems.

As we have more coordinates $\mathbf{q} \in \mathbb{R}^n$ than DoF, we use geometric constraints that provide the relation between these dependent coordinates. Hence, the corresponding mathematical model is a differential algebraic equation (DAE). The equation of motion is written in the general form:

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{C} + \boldsymbol{\varphi}_{\mathbf{q}}^{\mathrm{T}}\boldsymbol{\lambda} = \mathbf{H}\mathbf{u}\,, \tag{1}$$

$$\boldsymbol{\varphi} = \mathbf{0}\,, \tag{2}$$

where $\mathbf{M}(\mathbf{q}) \in \mathbb{R}^{n\times n}$ is a positive definite mass matrix. In case of natural coordinates, the mass matrix is constant $\mathbf{M}(\mathbf{q}) \equiv \mathbf{M}$, which is a relevant advantage. Vector $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) \in \mathbb{R}^n$ contains the centrifugal and Coriolis terms and all internal and external forces, including gravity. The holonomic and rheonomic geometric constraints are represented by $\boldsymbol{\varphi}(\mathbf{q}, t) \in \mathbb{R}^m$, thus the system has $n - m$ DoF. The Jacobian matrix $\boldsymbol{\varphi}_{\mathbf{q}} = \partial\boldsymbol{\varphi}/\partial\mathbf{q} \in \mathbb{R}^{m\times n}$ defines the direction of the constraint forces, while their magnitude are represented by the corresponding Lagrange multipliers $\boldsymbol{\lambda} \in \mathbb{R}^m$. The l dimensional control input vector is $\mathbf{u} \in \mathbb{R}^g$ and $\mathbf{H}(\mathbf{q}) \in \mathbb{R}^{n\times g}$ is the generalized control input matrix. By using the method of Lagrange multipliers extended by the Baumgarte stabilization, the DAE equations of motion are arranged in a form, which can be handled by an ODE solver:

$$\begin{bmatrix} \mathbf{M} & \boldsymbol{\varphi}_{\mathbf{q}}^{\mathrm{T}} \\ \boldsymbol{\varphi}_{\mathbf{q}} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}} \\ \boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} -\mathbf{C} - \mathbf{H}\mathbf{u} \\ -\dot{\boldsymbol{\varphi}}_{\mathbf{q}}\dot{\mathbf{q}} - \dot{\boldsymbol{\varphi}}_t - 2\alpha(\boldsymbol{\varphi}_{\mathbf{q}}\dot{\mathbf{q}} - \boldsymbol{\varphi}_t) - \beta^2\boldsymbol{\varphi} \end{bmatrix}, \tag{3}$$

where α and β are the Baumgarte stabilization parameters.

4 Control issues

During the development of the control framework, several problems raised, which are solved partly by the modification of the structural design of the prototype and partly from the side of the control.

4.1 Singularities

By using the classical orientation representations like Euler-angles, (nutation, precession, rotation) it is obvious to chose the zero nutation at the hanging down position. In this scenario, the precession is not unequivocal in the vertical position. By the application of natural coordinates based description the mathematical singularity can be avoided besides the aforementioned advantages.

The vertical configuration is singular also from control viewpoint in case of the first prototype (Fig. 2 left) which possesses only two ducted fan actuators generating a resultant force F_x in the direction of the tubes and a torque T_z around the vertical axis. Near to the hanging down position, the desired acceleration perpendicular to the thrust force requires sudden rotation of the SU about z. First, the solution was provided by the application of a secondary ducted fan in cross direction (Fig. 2 centre), and the final prototype design (Fig. 2 right) makes it possible to generate approximately the same magnitude of thrust forces (F_x and F_y) in any direction in the SU plane apart of the torque T_z. Consequently, the three pairs of ducted fan actuators represent 3 independent control inputs.

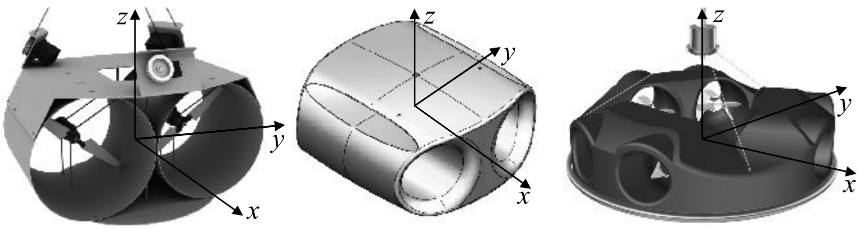

Figure 2. Evolution of the Swinging Unit: 2 ducted fans(left), additional cross direction fan (centre), 3 pairs of fans (right)

4.2 Underactuation

The complexity of the already intricate multibody control method is further complicated by the fact that the system is underactuated despite the large number of actuators, see Table 1. If the number g of the independent control inputs is less than the DoF of the system, then it is called *underactuated*, while if $g =$ DoF than the system is *fully actuated*. Recently, more and more robotic systems have utilized the advantages of underactuation, like agile motion and energy efficient operation. The part of the dynamics which cannot be controlled directly is called *internal dynamics*; here the horizontal position of the cable connector can not be controlled directly.

Unit	**DoF**	**Actuators**	**Prescribed DoF**
Climber Unit	3	3 (RRT)	$0 \mapsto 3$
Cable Connector	3	1 (MC)	$0 \mapsto 1$
Swinging Unit	6	6 (F_x, F_y, T_z, 3 SC)	6

Table 1. Degrees of freedom, actuators and prescribed DoF

4.3 Redundancy

The task of the robot is to keep the SU in the desired position and orientation in space, while there are no requirements for the motion of the CU and the CC. This means that the dimension of the task is only 6, all related to the SU only as the last column of Table 1 shows. Since the dimension of the prescribed task is smaller than the DoF, the robot is not just underactuated but also *kinematically redundant*. Since the notions of both kinematic redundancy and underactuation appear, we proposed a classification of the different combinations of these ideas (Zelei et al., June 12-15, 2012, Paris, France) as it is summarized in Table 2. *An underactuated manipulator equipped with more independent control inputs than required to perform a specified task is called dynamically redundant underactuated system.*

	underactuated	kin. redundant	dyn. redundant
DoF $= g = l$	no	no	no
DoF $> g = l$	yes	yes	no
DoF $> g > l$	yes	yes	yes

Table 2. Interpretations of redundancy (l - dimension of task, g - number of independent actuators)

In case of fully actuated robots, the above definition of dynamic redundancy is equivalent to the kinematic redundancy. In contrast, the inverse kinematics of underactuated systems cannot be solved uniquely without the consideration of the dynamics, so these are always kinematically redundant. However, if the task dimension l is equal to the number g of independent actuators, the determination of the control inputs is unique, and consequently the kinematics can also be calculated uniquely by using the internal dynamics. These systems are dynamically not redundant, the inverse dynamics can be solved uniquely. If the task dimension l is less than the number g of actuators, the system satisfies the above definition of dynamic redundancy, since even the inverse dynamic calculation is not unique.

The dynamic redundancy was resolved by the augmentation of the original set of tasks as Table 1 shows. The elevation of the CC was prescribed. The path of the main cable top mounting point was generated by a simplified model which utilizes the pendulum like motion. The inverse kinematics of the RRT structure was resolved by using geometric considerations.

4.4 Control algorithm

In spite of the underactuation, the system can be controlled by an extended inverse dynamical method. With the generalization of the method of Lagrange multipliers (3) the prescribed path of the robot is also defined as additional holonomic and rheonomic constraint equations called *servo-constraints* or *control-constraints* (Blajer and Kolodziejczyk, 2007, From the issue entitled "Dynamical Systems: Theory and Applications"; Kovács et al., August 28 - 31, 2011, Washington, USA):

$$\boldsymbol{\sigma} = \mathbf{0}; \quad \boldsymbol{\sigma}(\mathbf{q}, t) \in \mathbb{R}^l. \tag{4}$$

The task has same dimension as the number of independent control inputs l, consequently the above-mentioned dynamic redundancy is avoided. The geometric and servo-constraints are *linearly independent* and also *consistent*, that is, there are no contradictory constraints, and they can be satisfied with *bounded control input*. The application of natural coordinates improves the solvability of the inverse kinematic problem, and the servo-constraints can be given conveniently.

The inverse dynamical calculation determines the desired acceleration $\ddot{\mathbf{q}}$, the input $\mathbf{u}$ and adjunctively the vector $\boldsymbol{\lambda}$ of Lagrange multipliers uniquely, which satisfy the DAE system (1), (2) and (4). We extend the method of Lagrange multipliers (3) by including the control input $\mathbf{u}$ which plays the role of the corresponding Lagrange multipliers of the servo constraints $\boldsymbol{\sigma}$:

$$\begin{bmatrix} \mathbf{M} & \boldsymbol{\varphi}_{\mathbf{q}}^{\mathrm{T}} & -\mathbf{H} \\ \boldsymbol{\varphi}_{\mathbf{q}} & \mathbf{0} & \mathbf{0} \\ \boldsymbol{\sigma}_{\mathbf{q}} & \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}} \\ \boldsymbol{\lambda} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} -\mathbf{C} \\ -\dot{\boldsymbol{\varphi}}_{\mathbf{q}}\dot{\mathbf{q}} - \dot{\boldsymbol{\varphi}}_t \\ \dot{\boldsymbol{\sigma}}_{\mathbf{q}}\dot{\mathbf{q}} - \dot{\boldsymbol{\sigma}}_t - D(\boldsymbol{\sigma}_{\mathbf{q}}\dot{\mathbf{q}} - \boldsymbol{\sigma}_t) - P\boldsymbol{\sigma} \end{bmatrix}, \tag{5}$$

where P and D are proportional and derivative gains of the linear compensator and play a similar role as Baumgarte gain parameters α and β. The stabilization of the geometric constraints is unnecessary, because the geometric constraints are satisfied naturally, when the measured coordinate values are substituted.

5 Summary

The Acroboter domestic robot concept utilizes the advantages of both flying robots and crane-like systems. The problems of obstacle avoidance and energy efficiency are resolved together, furthermore, the robot platform utilizes the pendulum-like motion efficiently and provides large vertical workspace while it is still lightweight. As a secondary result of the development process of Acroboter we elaborated a general model-based motion control algorithm for underactuated and redundant multibody systems. The control approaches were tested and applied in laboratory experiments for the Acroboter prototype.

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