Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 48-11 (2015) 156–161

An integrated control-structure design for manipulators with flexible links

Guaraci Bastos Jr. * **Olivier Brüls** **

* *Federal University of Pernambuco, Department of Mechanical Engineering, Recife, Brazil (e-mail: guarajr.bastos@gmail.com).*
** *University of Liège, Department of Aerospace & Mechanical Engineering, Liège, Belgium (e-mail: o.bruls@ulg.ac.be)*

Abstract: Integrated optimization techniques for mechatronic systems aim at designing simultaneously the trajectory, the control system and the mechanical structure in order to minimize a performance index. The key advantage of such an integrated approach is the capability to search in a wide design space, to account for many dynamic couplings in an early design stage and to avoid simplifying assumptions which would induce a suboptimal design. This work considers that technique for robotic manipulators with flexible links. It is known that a flexible multibody system is often non-minimum phase, here, no restriction is imposed to avoid it. This allows a free choice of the optimization process to select a lighter weight controlled system. Furthermore, the amplitudes of the non-actuated degrees-of-freedom should be reduced in order to limit bodies deformation. The mechanical model is derived using a nonlinear finite element method, which is a useful approach to represent systems with elastic bodies. An optimal control problem is considered to perform that integrated analysis and its time dicretization relies the direct transcription method.

Keywords: Integrated optimization, optimal control, multibody systems, flexible manipulators, finite element method, control-structure design.

1. INTRODUCTION TO MECHATRONIC OPTIMIZATION

The design of lightweight machines and robots for high-speed industrial applications is usually driven by the necessary compromise between the weight of the moving structural components and their inherent structural flexibility. Most approaches try to avoid any interference between the vibrations of the system and the controller dynamics. However, several authors Da Silva et al. (2009a); Ravichandran et al. (2006); Rieber and Taylor (2004); Van Amerongen (2003); Van Brussel (1996) have pointed out that this design approach only leads to suboptimal dynamic performances. This motivates the development of a more integrated design framework, where the mechanical components and the control system can be simultaneously analysed and optimised. The objective of this study is to contribute to the development of multidisciplinary modelling and optimization tools in order to address this mechatronic design problem.

Techniques and algorithms for structural optimization were studied and developed for a long time considering static or quasi-static loads. Comparatively, applications that consider dynamic loads, including structural vibrations or a flexible multibody motion driven by a control system, represent an increased level of difficulties. Bendsoe and Sigmund (2003) pointed out that the optimal design may be very sensitive to the supports and loading conditions. Sequential techniques represent a classical approach to solve the structural optimization in a dynamic context. It is based on a static optimization where the state-of-art is well developed. For example, the equivalent static load method is a sequential technique, which relies on two steps, see, e.g., Bayo and Ledesma (1997); Haussler et al. (2004); Hong et al. (2010). In the first step, the dynamic loads are computed and, in the second step, the components are optimized independently based on a set of equivalent static load cases which mimic the pre-computed dynamic loadings. The advantage of this technique is that the optimization step can exploit well-developed and mature approaches for the optimization of static structures. However, this approach can hardly be used to minimize a truly dynamic index of performance and it is not appropriate if the dynamic loads are strongly design-dependent, which is the case, e.g., for inertia loads.

In a mechatronic system, the loads exerted on the structural components depend not only on the structural design but also on the control excitation. Conversely, the design of the control law requires a detailed knowledge of the structural behaviour. For these reasons, the optimal design of mechatronic systems requires the development of highly integrated procedures. The integrated design of a multibody system and its feed-back controller was addressed in Da Silva et al. (2009a,b,c). Da Silva et al. (2009b) studied the integrated optimization of a machine-tool with a gripper carried by a flexible beam. A reduced-order model of the mechanical system is obtained using the global modal parameterization method Brüls et al. (2007) and a linear parameter varying controller is derived using an interpolation of local controllers based on the reduced models.

10.1016/j.ifacol.2015.09.176

The inverse dynamics problem appears particularly difficult to solve for underactuated/flexible multibody systems, see Bastos et al. (2013); Brüls et al. (2014), where there are less control inputs than degrees of freedom. In this case, non-actuated degrees-of-freedom are present and their trajectory is named internal dynamics. The control of elastic manipulators was also adressed in Chernousko et al. (1994).

Besides, the integrated optimization of underactuated multibody systems considering structural parameters and feed-forward control inputs has been studied in Seifried (2012). In this reference, the main objective was to design a minimum phase system, which is expressed by a relevant optimization criteria, by modifying geometric dimensions and mass distributions of the system. Since a minimum phase systems has a stable internal dynamics, it can be controlled using a feed-back linearisation method. A particle swarm optimization procedure was used in that work.

The present work investigates the integrated optimization of controlled flexible multibody systems. The structure, the internal trajectory and the actuator forces (feed-forward control) are simultaneously considered in the optimization process. In other words, the integrated optimization includes structural optimization and inverse dynamics analysis. No restriction is made on the stability of the internal dynamics, so that the mechanical system can be chosen quite freely. Therefore, non-minimum phase systems can be considered and non-causal solutions to the inverse dynamics problem need to be taken into account.

The mechanical model is derived using the nonlinear finite element method Géradin and Cardona (2001) and the index−3 DAE form of the equations of motion are solved in the time domain using the generalized-α method Arnold and Brüls (2007); Chung and Hulbert (1993), which is a generalization of the Newmark method. Following the direct transcription method, the optimal control problem is transformed into a large but sparse nonlinear programming problem. The equations of motion, the time integration formulae and the trajectory constraints are treated as equality constraints. The sparse gradients of the optimization constraints are computed using a semi-analytical method.

2. INTEGRATED OPTIMIZATION OF MULTIBODY SYSTEMS

Figure 1 shows the block diagram of a controlled dynamic system, whose mechanical design depends on a set of structural parameters $\mathbf{p}$, with a feed-forward control part and a feed-back control part. In the following an off-line analysis is performed, the feed-back term is not considered, and then $\mathbf{u}(t) = \mathbf{u_{ff}}(t)$. The design problem is to find both the optimal control inputs $\mathbf{u_{ff}}$ and the optimal set of structural parameters $\mathbf{p}^*$ of a flexible multibody system, under the constraint of tracking a specified trajectory $\mathbf{y_d}(t)$.

A finite element method is considered to formulate the mechanical model of the flexible multibody system. This is based on the geometric exact nonlinear formulation Géradin and Cardona (2001). The equations of motion of a multibody system in absolute coordinates, with trajectory constraints, take the general form

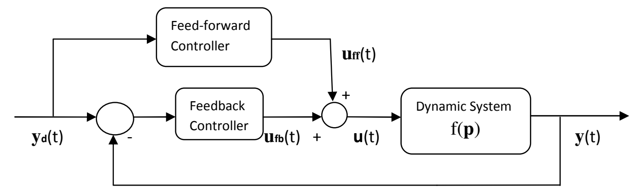

Fig. 1. Control block diagram: dynamic system in function of geometric parameters $\mathbf{p}$

$$\mathbf{M}(\mathbf{q},\mathbf{p})\ddot{\mathbf{q}} + \mathbf{g}(\mathbf{q},\dot{\mathbf{q}},\mathbf{p},t) + \mathbf{B}^T(\mathbf{q})\boldsymbol{\lambda} - \mathbf{A}\mathbf{u} = \mathbf{0} \quad (1)$$

$$\boldsymbol{\Phi}(\mathbf{q}) = \mathbf{0} \quad (2)$$

$$\mathbf{y}(\mathbf{q}) - \mathbf{y_d}(t) = \mathbf{0} \quad (3)$$

where $\mathbf{q}$ is the vector of r absolute coordinates, $\mathbf{p}$ is an additional element, which includes w structural design parameters, $\mathbf{M}$ is the mass matrix, $\mathbf{g}$ is the vector of internal and complementary inertia forces, $\boldsymbol{\Phi}$ is the vector of m kinematic constraints, $\boldsymbol{\lambda}$ is the vector of m Lagrange multipliers and $\mathbf{B} = \partial\boldsymbol{\Phi}(\mathbf{q})/\partial\mathbf{q}$ is the matrix of constraint gradients. The input matrix $\mathbf{A}$ distributes the s control inputs $\mathbf{u}$ onto the directions of the system coordinates, whereby $\mathbf{A}$ is often a constant matrix. The s trajectory constraints are represented by Eq. (3), where the operator $\mathbf{y}(\mathbf{q})$ computes the outputs of the dynamic system and $\mathbf{y}_d(t)$ represents the prescribed path.

In the present case, the dynamics of the system changes during the optimization process. It means, the eigenfrequencies $\omega_n = \omega_n(\mathbf{p})$ changes at each iteration. A problem is to lead with very high frequencies during the iterative process, because it induces to numerical difficulties.

Let us consider that the problem is to minimize an objective function with a general *Bolza* form, in our particular case :

$$J = \int_{t_i}^{t_f} L(\mathbf{q}(t),\mathbf{u}(t))\,dt + E(\mathbf{q}(t_f),\mathbf{p}) \quad (4)$$

In general, path constraints and termination constraints impose restrictions to the dynamics of the system. In this work, no termination constraints are considered but Eqs. (1-3) and the time integration based on generalized-α method, Chung and Hulbert (1993), are treated as path equality constraints which are written in compact form as

$$\mathbf{c}(\mathbf{q}(t),\dot{\mathbf{q}}(t),\ddot{\mathbf{q}}(t),\boldsymbol{\lambda}(t),\mathbf{u}(t),\mathbf{p}) = \mathbf{0}, \quad \forall t \quad (5)$$

Here, bounds on the values of the structural design parameters $\mathbf{p}$ are needed, to avoid the situation of a vanishing structure, for example.

$$\mathbf{v}(\mathbf{p}) \geqslant \mathbf{0} \quad (6)$$

where the termination inequalities constraints are imposed component-wise.

2.1 Direct transcription method

In this direct method, the optimal control problem is discretized in time with N grid points $t^{(k)}$, $k = 1,\ldots,N$. For a dynamic system represented by Eqs. (1-3), the generalized-α method is used to discretize the problem in time. The set of design variables $\mathbf{x}$ includes at each