Influences of the mechanical structure of a 'goliath' robot on different controlling strategies

A. Arenz, E. Schnieder
Institute of Control and Automation Engineering
Technical University of Braunschweig
Langer Kamp 8, D-38106 Braunschweig, Germany
Phone: +49-531/391-9790, Fax: +49-531/391-5197
E-mail: a.arenz@tu-bs.de

Abstract

Background. To increase the capacity of modern goods transport new and efficient concepts are necessary. In this connection the Institute of Control and Automation Engineering at the Technical University of Braunschweig has developed a new transfer module for transshipping container from trains to trucks and vice versa. Especially challenging are the influences of heavy weight goods on the robot structure.
Methods. Parallel to tests on a prototype model in the scale 1:8 thorough simulation studies are performed. As simulation environments different tools are available:

- ADAMS is used to investigate the influences of different mechanical structures and to optimize the whole system whereas
- MATLAB is taken to design control algorithms and to plan optimal tracks etc.
- ANSYS is needed to include elastic bodies.

Furthermore it is interesting to interface the different software tools.
Results. In this paper a simple model of a transfer robot is presented. The focal points are the influence of heavy weights and possible resulting concepts. Controlling strategies dealing with these problems are presented. Obtained simulation results are shown and discussed critically.

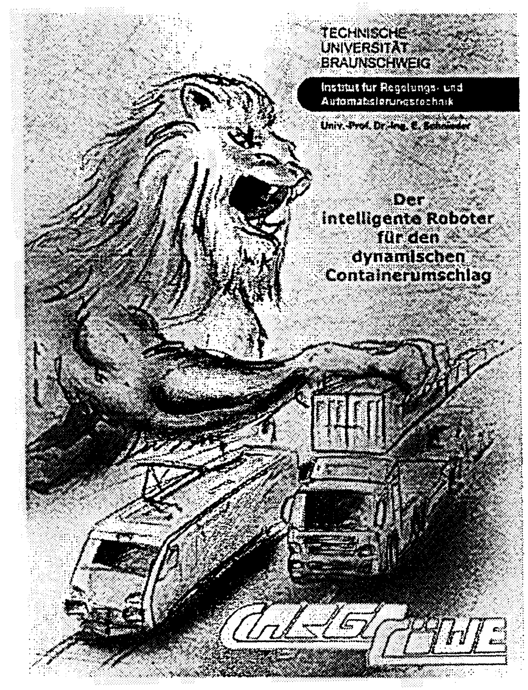

Figure 1: CargoLoewe: The intelligent robot for dynamic container handling

Keywords. Influences of heavy weights, 'goliath' robot, combined goods transport, ADAMS - MATLAB interface, adaptive control.

Introduction

During the last years the traffic situation not only on German but also on European highways has worsened. Traffic jams are regular daily 'phenomenons'. Trucks offer a cheap and reliable means of transportation with a high flexibilty in the local traffic and are therefore the first choice of most customers. Trains as another transport media have a larger long distance transport capacity together with good ecological and economical balances but are not competitive so far. The concept of the combined goods transport now tries, as its name promises, to combine several means of transportation. Like in many applications the weak point is the intersection

where the goods have to change the transport media.
The Institute of Control and Automation Engineering is engaged in this subject since several years. The aim is to develop a transfer module

which directly transfers moving goods between different transport media,
which transfers goods moved at a certain velocity and
which transfers goods in presence of obstacles.

The process itself is characterized by a few main attributes: The objects to be handled, which are different container types, weigh up to 35 tons. The time span for one cycle should be much less than one minute. The transport media (e.g. a train) moves at about 2.5 km/h. It should be possible not only to build new fully automated terminals but also to integrate the component 'robot' in existing stations. This target requires a highly modular concept.
The first phase consisted mainly of conceptional studies resulting in a model of a terminal in the scale 1:45 as shown in fig. 2.

Figure 2: Model of the 'Container Terminal 2000' (M 1:45)

In further studies the concept of the transfer robot is investigated in detail. The final aim is the construction of a prototype robot in the scale 1:8. Thorough simulation studies are performed which preceed and supplement the experimental investigations (see [3]) . Different development stages can be distinguished:
Initially the existing concept was validated and modified accordingly. Clippings of an animation are shown in fig. 3.

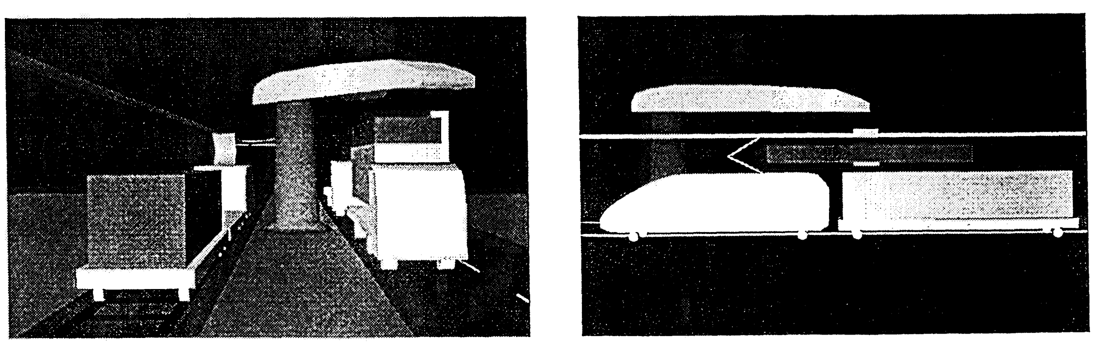

Figure 3: Animation of the 'goliath' robot (M 1:1)

Based upon these results a simulation model in the scale 1:1 is designed and tested. Especially questions concerning the influence of the heavy weights are observed as the whole system is dominated by these effects. Afterwards in a verification step the simulation model is transfered to the scale 1:8 and compared with the prototype structure. Possibly parts of the robot will be build in the scale 1:1 as well in order to obtain more accurate results.

System modelling - tool interfacing

In the wide field of Mechanical Computer-Aider Engineering (MCAE) many different starting points exist and complement one another like Mechanical System Simulation (MSS), Control System Design, Structural Analysis, Computer Aided Design (CAD), Optimization or Animation. One main problem is to join all the different products, which are often designed only for one special target. The objective should be to create a model only once. Afterwards an automatic portation facility to the different systems is desirable.

For the simulation of the robot different complementary tools are used, namely

ADAMS for the design of the mechanical system,
MATLAB for the controller design and
ANSYS for the structural analysis.

Useful are the existing interface structures. For completeness the methods applied are mentioned (see [2]):

1. integrating flexible bodies (from a FE tool) in a (rigid) mechanical system environment
2. exchanging linearized state space matrices with a control tool
3. running programs like Adams and Matlab interactively
4. programming subroutines (e.g. in C)

In this paper the sense of looking at a problem from different point of views and directly exchanging the obtained results shall be demonstrated. At the given example it is discussed how the influence of heavy weights can be found out on the one hand and on the other hand how these effects can be controlled. In order to separate different phenomenons only the rigid body motion is considered in the following.

The mechanical system 'robot'

Process simulation results

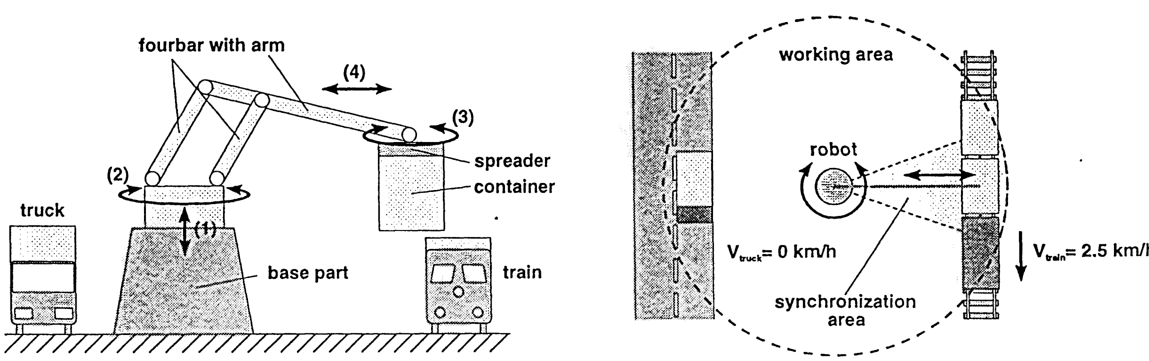

Figure 4: The robot structure

The principal robot setup is shown in fig. 4. Four main motions can be distinguished: the vertical motion (1) in the base part to lift a container, one rotational (2) motion to swing from a train to a truck and back, another rotational (3) one to turn the container around its own vertical axes and the fourbar structure (4) to describe a horizontal line movement. The last motion is necessary in order to synchronize the spreader of the robot with the moving train.

In fig. 5 a reduced model is shown where the fourbar is reduced to a single arm. The reduced model has several advantages. It combines a relative easy design with nearly the full functionality. Furthermore the derived consideration can be applied on other robot structures, too (e.g. a telescopic arm).

The following reflections will concentrate on the rotational movements of the arm and the spreader. The drives consist each of a motor and a gear unit. It shall not be explicitly defined whether to use electric or hydraulic machines. A gearing is necessary in any case in order to

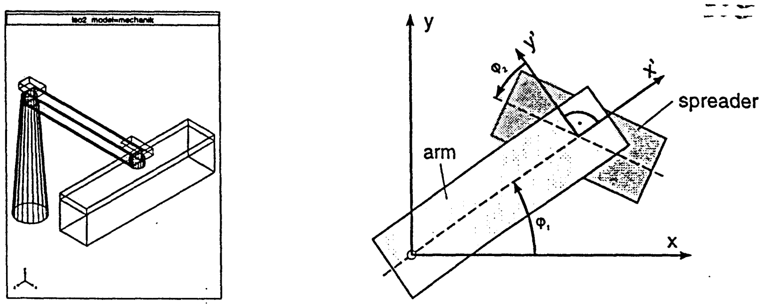

Figure 5: The reduced robot structure with the definitions of the angles used

improve the resolution.
Next the influence of container, motor and gear on the arm and the spreader position are considered (see fig. 6 and 7).

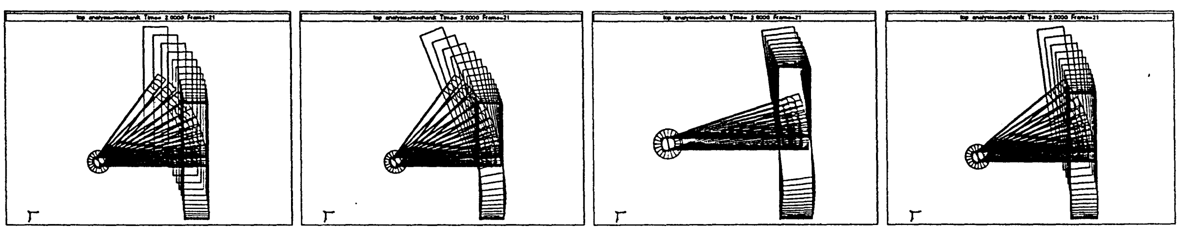

Figure 6: Drive on φ_1: simple case (a), with extension gearing masses (b), with different gear ratio (c), with container mass (d), (from left to right)

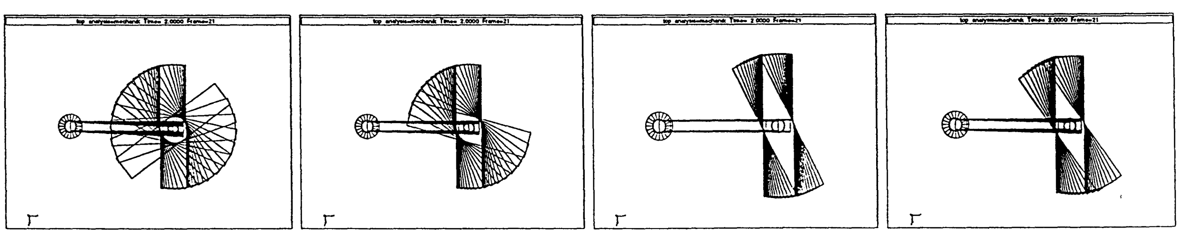

Figure 7: Drive on φ_2: simple case (a), with extension gearing masses (b), with different gear ratio (c), with container mass (d), (from left to right)

Following assumptions are made: a square profile (1 m x 1 m x 10 m x 0.02 m) is used for the arm. The spreader weighs 15 t (homogeneous density), a container weighs max. 30 t, motor 1 and 2 weigh up to 400 kg, the gears up to 200. The gearing ratios vary from 1 to 10^{-3} for the arm and 1 to 10^{-2} for the spreader, the motor moment goes up to several kNm. The angle of the arm φ_1 and of the spreader φ_2 are defined as shown in fig. 5.
In the simple case (6a) gear and container masses are omitted. The arm is turned according to the applied force. The spreader performs a relative movement around the arm so that no absolute motion is obtained. When including gear masses in the system (6b) the spreader motion results in a slow rotation due to the gear inertia which has to be overcome. Reducing the gear ratio (6c) of the system (factor 10) results in a slower movement. A similar reaction is obtained when a container is additionally grabbed (6d). Now observing the motor force on the spreader (fig. 7) an interesting effect is the coupling reaction on the arm (7a). It occurs due to the bearing forces from the gearing on the arm. Besides the same conclusions can be drawn as in the first case. The gear ratio for the second motor can be about ten times smaller.

State space equation of the process

Using for example Lagrange or d'Alembert principle the following system equations can be derived. Neglecting friction effects coupled double integrators with the input forces u_1 and u_2 are obtained for each angle φ_1 and φ_2.

$$\underbrace{\begin{pmatrix} \ddot{\varphi}_1 \\ \dot{\varphi}_1 \\ \ddot{\varphi}_2 \\ \dot{\varphi}_2 \end{pmatrix}}_{\dot{x}} = \underbrace{\begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}}_{A} \underbrace{\begin{pmatrix} \dot{\varphi}_1 \\ \varphi_1 \\ \dot{\varphi}_2 \\ \varphi_2 \end{pmatrix}}_{x} + \underbrace{\begin{bmatrix} b_{11} & b_{12} \\ 0 & 0 \\ b_{31} & b_{32} \\ 0 & 0 \end{bmatrix}}_{B} \underbrace{\begin{pmatrix} u_1 \\ u_2 \end{pmatrix}}_{u} \qquad (1)$$

$$\underbrace{\begin{pmatrix} y_1 \\ y_2 \end{pmatrix}}_{y} = \underbrace{\begin{bmatrix} 0 & c_{12} & 0 & 0 \\ 0 & c_{22} & 0 & c_{24} \end{bmatrix}}_{C} \underbrace{\begin{pmatrix} \dot{\varphi}_1 \\ \varphi_1 \\ \dot{\varphi}_2 \\ \varphi_2 \end{pmatrix}}_{x} \qquad (2)$$

Hence the resulting equations are

$$\ddot{y}_1 = \underbrace{[b_{11}c_{12}]}_{1/I_1} u_1 + \underbrace{[b_{12}c_{12}]}_{1/I_2} u_2 \qquad (3)$$

$$\ddot{y}_2 = \underbrace{[b_{11}c_{22} + b_{31}c_{24}]}_{1/I_3} u_1 + \underbrace{[b_{12}c_{22} + b_{32}c_{24}]}_{1/I_4} u_2 \qquad (4)$$

The coefficients of the output matric C are given by the gear ratios n_1 and n_2

$$c_{12} = n_1 \quad , \quad c_{22} = -n_1 n_2 \quad , \quad c_{24} = n_2 \qquad (5)$$

whereas the generalized inertia moments are computed to

$$I_1 = n_1 \left[\frac{1}{n_1{}^2} J_{g1} + (\frac{1}{4} m_{arm} + m_{spr} + m_{m2} + m_{g2}) l^2 + J_{arm} \right] \qquad (6)$$

$$I_2 = \frac{-n_2}{1 - n_2} \left[\frac{1}{n_1{}^2} J_{g1} + m_{arm} \frac{l^2}{4} + m_{g2} l^2 + J_{arm} \right] \qquad (7)$$

$$I_3 = I_2 \qquad (8)$$

$$I_4 = \frac{n_2 J_{spr} I_2}{n_2 J_{spr} + I_2} \qquad (9)$$

with the masses m, the inertia moments J, the length of the arm l and the short cuts $_{arm}$, $_{spr}$, $_m$ and $_g$ for arm, spreader, motor and gear.

The number values can be directly obtained using the Adams/Linear option, so that the given equations can be verified and easily calculated for different parameter studies.

Especially interesting is the influence of a heavy container. The additional mass is assumed to be 40 tons. To estimate the maximal changes of the system parameters the following reflections are made. The container mass can be directly added to the spreader mass as both parts are supposed to have the same vertical center point. Eq. (6) is mainly dominated by the inertia moment of the arm (which is about ten times higher as the masses of spreader and container) and the inertia moment of the first gearing (which is multiplied by the inverse of the gear ratio). Consequently only at known arm dimensions and gearing and in combination with a high measurement resolution the container mass can be identified and calculated exactly. The relative percental divergence of the system with and without container mass is 8 %. Eq. (7) and (8) which include the coupling terms shall not considered. In eq. (9) the moment of inertia is a direct multiplier. Here the relative percental difference is about 50 % and goes up to 73 % for lower gear ratios at gear 2. This means that with container the system parameters are about 3.7 times higher than without an additional mass. The factor is be approximately given by the fraction $(m_{spr} + m_{cont})/m_{spr}$.

The controller design - adaptive control

It is easy understandable that the great variation of the process parameters influences the control of the system negatively and renders its design more difficult.
One possible solution is to lower the dynamic of the controller so that stable characteristics are obtained. Of course this raises the settling time of the system. Further more the controller - probably optimized for a middle weight - will have some problems positioning the heavy weights which are more difficult anyway.
When, like in the present case, the dynamic process model is available another solution presents itself. It is called adaptive control because the controller parameters are adapted corresponding to the behaviour of the system.

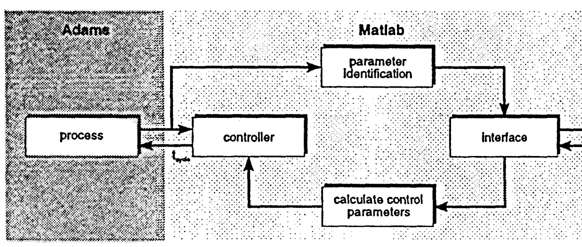

Figure 8: The adaptive control structure interfacing Adams and Matlab

The control structure is composed of two separate sections, the process identification and the calculation of the control parameters, which are connected at an interface point (see fig.8). Basis of the identification are measurements of the in- and output signals of the process. Necessary stimulations of the process can be guaranteed because the fast robot motions resemble a step function. Using a recursive least squares algorithm an online identification is possible. Next knowing the process parameters an optimal controller can be designed. Good and fast results are obtained using an optimal state control (LQR or LQG).
In the process under consideration it may as well be possible to calculate the container mass attached to the spreader using the equations from above. Control parameters are now optimized in advance and stored in a lookup table. This proceeding also guarantees a sensible controller, as the calculated mass can be verified easily. Furthermore it can be compared with other (necessary) measurements concerning the spreader.
More detailed information on the theory of adaptive control is given in [1].
Some simulation results are presented in fig. 9. As input signal a step spline function is used. The 'standard' LQG controller (dotted curve) is optimized for a medium weight whereas the adaptive controller (solid curve) tunes itself according to the weight. A short identification period of 0.25 s and a longer one of 1 s are distinguished.
The following statements are obtained. The LQG-controller shows positive results in both cases (u.l.). The step deviation is controlled in about 2 s. The adaptive controller has an improved behaviour with a shorter settling time and less deviation. The maximum regulator energy is similar (u.r.). The obtained adaption quality is very good (l.l., l.m.) especially for the higher adaption time (l.r.).
So far the controlling results are only obtained under Matlab. In future investigations it will be tried to include the controller in the (nonlinear) mechanical system given by Adams. As the identification and adapting algorithms are very complex it is not possible

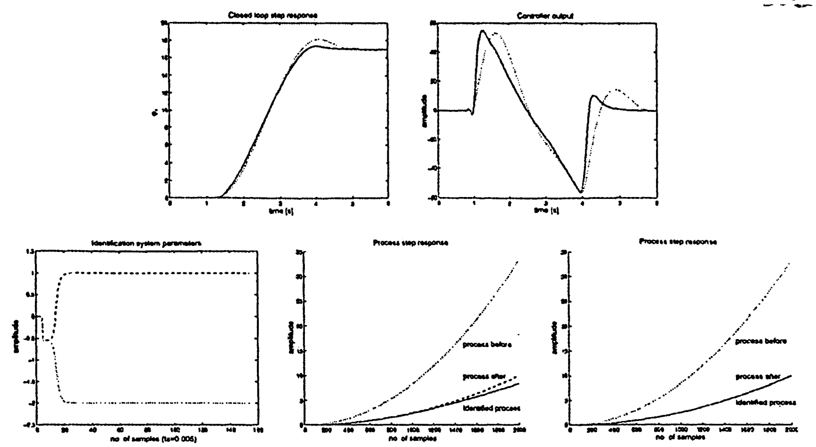

Figure 9: Step response (u.l.), regulator energy (u.r.), parameter identification (l.l),

to use the 'offline' interface and only exchange the state space matrices. Instead running both programs, Adams and Matlab, simultaneously and exchanging the variables at a certain cycle time (as shown in fig. 8) seems a natural choice. It would also be possible to transform the matlab files in C-code and include these files as user-subroutines in Adams.

Outlook

Up to now only rigid body motions were discussed. As mentioned at the beginning of the paper this can only be the first step. Fig. 10 shows the deflections of the flexible arm when a container with a mass of 40 tons is lifted. Obviously these effects can not be neglected.
Now using the Adams/Fea interface it will be tried to include elastic parts so that a hybrid mechanical system results. The final aim is to automatically generate the elastic system equations similarly to the proceeding for rigid systems which is shown in this paper.

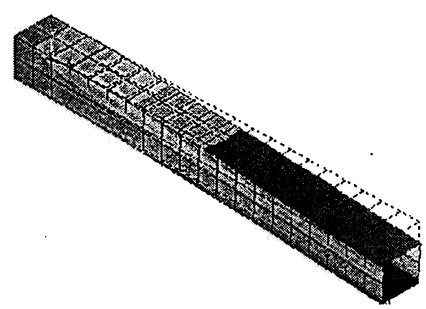

Figure 10: The flexible arm

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