Path Generation for a Redundant Sensor Guided Unloading Crane

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Abstract: The path generation for a redundant sensor guided coal unloading crane is discussed in this paper. After using much of task specific knowledge to restrict the possible Tool Center Point (TCP) trajectories to a feasible subspace, two approaches are analyzed to optimize the dig head trajectory in this subspace: a Fuzzy Logic and a Dynamic Programming based trajectory generation. Experimental results are presented for a CCD-camera guided hydraulic manipulator tracking an optimized unload trajectory.
Keywords: Trajectory Planning, Robotics, Fuzzy Logic, Dynamic Programming.

1. Introduction

To obtain greater productivity and reliability a lot of processes are being automated using robotic manipulators. As quality specifications are tighter the use of sensor guided manipulators can improve the interactibility of the robot with its environment, providing greater flexibility.

Redundant manipulators are characterized by more than six degrees of freedom. This yields greater flexibility to meet special requirements, presented e.g. in [Höfer, 1992], [Bauchspiess, 1995]. One set of all joint variables (angles for rotational or lengths for prismatic joints) define a unique position and orientation of the manipulator and is called a *configuration*.

So called "*intelligent controllers*" have been proposed to simplify the design of guidance controllers, e.g. [Vaneck, 1997]. But rarely they are compared with classical "*optimal*" controllers for real implementations. In this paper the automatic generation of paths for a sensor guided redundant coal unloader crane is discussed. The goal is to unload a euro-coal-ship by a continuously working conveyor belt crane which is only supervised by a crane operator. After reducing the possible trajectories that can perform the task in a feasible trajectory subspace by using a priori knowledge, two approaches for optimizing the trajectory of the dig head in a feasible subspace are compared: an "*intelligent*" Fuzzy Logic based path generator and an "*optimal*" Dynamic Programming based system.

2. Structures of trajectory generators

A path generator system can be classified, according to the strategy of the joint reference generator, in:

Stored Trajectory (Play-Back)

This is the most commonly encountered situation for real-world robot systems. The path trajectory is known (e.g. acquired in a teach-in procedure) and only minor corrections will be done during the execution phase. The data may also be provided by a CAD system (off-line programming), and the trajectory generator only needs to verify the realizability of the demanded task. In most cases some on-line interpolation is needed to generate the real-time reference values for the joints based on the stored trajectory points. Very often the *spline* interpolation is used [Wurmthaler, 1994].

Sensor Guiding

In this case the trajectory describing the task must be obtained *on-line* from measured sensor data. The sensors should be mounted in order to get look-ahead information. This information can then be used in a predictive controller to minimize the tracking error [Bauchspiess, 1995].

Task Optimization

In this situation only a task definition is given to the automation system, e.g. "unload the coal ship". The trajectory that performs must be obtained using a-priori knowledge in conjunction with sensor data. This case will be investigated for a sensor guided redundant coal unloader in this paper.

3. The continuous coal unloader

In traditional batch coal unloading very much time and energy is wasted turning the entire crane forth and back, Fig. 1.

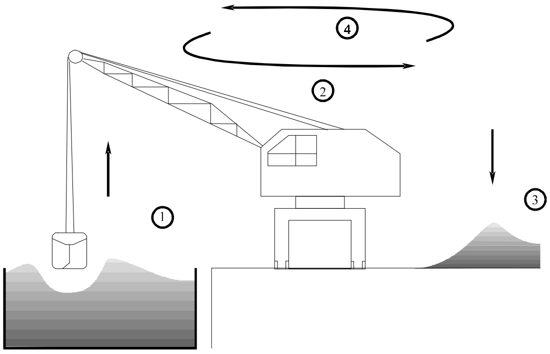

Fig. 1 Traditional batch coal unloading: 1-Coal capture, 2-Transport to haven, 3-Coal discharge, 4-Back to ship.

To optimize the unloading process the continuously working conveyor belt crane schematically shown in Fig. 2 was developed [MAN, 1991]. Here only a dig head and a double conveyor belt faced arm (needed for the vertical coal transport) are moved over the coal surface to capture coal into the conveyor belt system.

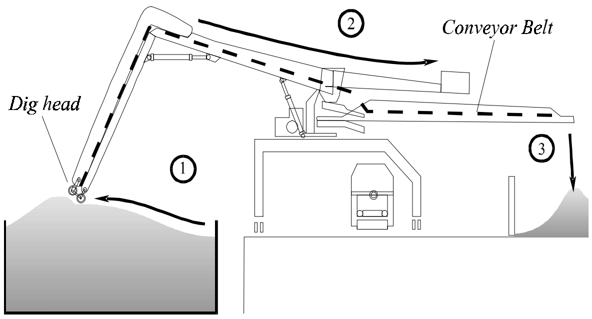

Fig. 2 Continuous coal unloader: Dig head + Conveyor belt system: 1- Capture, 2- Transport, 3- discharge.

Equipping the dig head with sensors, (e.g. ultrasonic distance sensors, which can work in dusty environments) as shown in **Fig. 3**, one obtains the information needed for a stand alone autonomous unloading system. During the unloading process the sensors capture the actual coal surface, and this information is then used by the trajectory generator system to calculate the Tool Center Point (TCP) trajectory for the next planning horizon.

The ship can be unloaded removing layer after layer by traversing the dig head forth and back while moving the entire crane along the ship on a rail system [MAN, 1991]. The automation system should control the unloading crane such that properly chosen coal slices are carried out in each traverse, as shown in **Fig. 4**. Obviously, the ship will be empty after a sufficient number of coal layers have been removed.

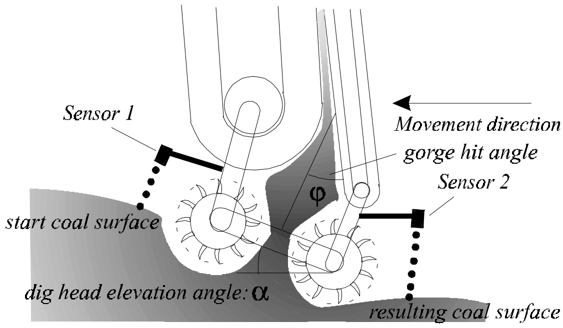

Fig. 3 Disposition of ultrasonic sensors at the dig head. In this figure sensor 1 foresees the coal surface, sensor 2 captures the resulting coal surface.

4. Feasible trajectory subspace

The trajectory generation for redundant manipulators can be formulated as a optimization problem. The best trajectory for the TCP and for the other degrees of freedom will be determined using optimization criteria and existing boundary conditions.

When considering the coal unloading process, the first optimization criterion coming in mind would probably be a minimization of the unloading time. But looking closer to the problem, another criterion seems to be more advantageous. Since the conveyor only carries a nominal load, it would be a waste of resources to move the TCP faster or deeper than required for this nominal load. Indeed, when this nominal load can be provided in a suitable subspace of the realizable trajectory space, then for all these trajectories the unloading time will be a constant, namely

$$T_{unload} = \frac{V_{Shipload}}{Q_{Nom}} \frac{[m^3]}{[m^3/s]}, \qquad (1)$$

where $V_{shipload}$ is the total coal volume contained in the ship, and $Q_{Nom}$is the nominal load rate of the conveyor belt.

So we conclude that the optimization of the unloading trajectory should consider other objectives than simply reducing the unloading time.

A suitable criterion is based on the energy used in the crane operation, taking into account given geometrical/mechanical restrictions - resulting forbidden positions of the paddle-wheels (describable by the dig head elevation angle alpha, Fig. 3), when traversing. Fig. 4 shows the cross section profile after the first forward traverse as well as the path of the TCP. The resulting new surface is obviously non-symmetrical, Fig. 5.

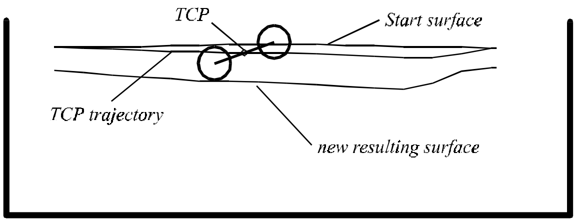

Fig. 4 Modification of the coal surface by the dig head in an axial ship view.

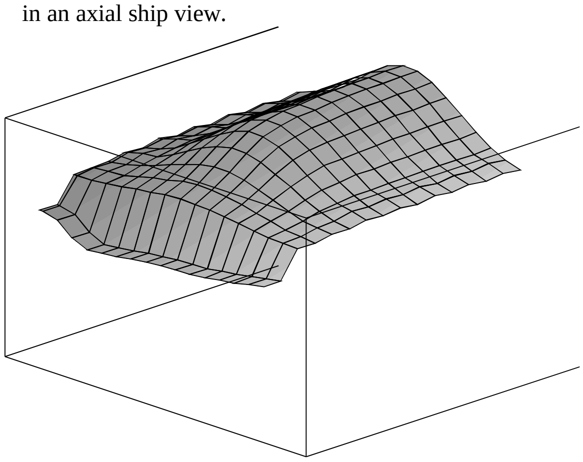

Fig. 5 Coal surface after the first unloading traverse.

So it is better to consider a complementary unloading strategy that comprises forward and back traversing, for a same position of the crane along the ship on the rail.

5. Optimization of the unloading trajectory

Two approaches that can be used to obtain optimal trajectories to empty the ship in the feasible subspace will be considered in this paper. One approach is fixing the remaining degree of freedom of the redundant manipulator by establishing the dig head elevation angle for each traverse position by a fuzzy inference system. This leads to a unique unloading sequence of configurations, and will be considered next.

5.1 Fuzzy Logic path generation

If a fixed dig angle is used in a traverse inefficient conveyor belt feeding arises, due to inherent mechanical restrictions of the redundant unloading crane (Fig. 3).

The dig angle can be obtained considering the following Fuzzy ***Rule Basis*** Fig. 3:

1. Good conveyor belt feeding is obtained at α=25°. In this case both the paddle-wheels are in a proper position,
2. Good conveyor belt feeding is obtained at φ=0°. In this case the bulk material jet is parallel to the gorge and the coal (theoretically) can be transported by the conveyor belt without losses,
3. Due to mechanical restrictions the dig angle near the ship wall should be 15°,
4. At the end of a traverse the dig angle should be about 0 degree in order to prepare the backward traverse.

As a result of this Fuzzy trajectory generator we find unloaded bulk material (rest coal hills) near the walls of the ship (Fig. 7). The reason is the local aspect of the Fuzzy strategy - not considering the complementary nature of the forward and backward movement (“from haven” - “to haven”) of the crane.

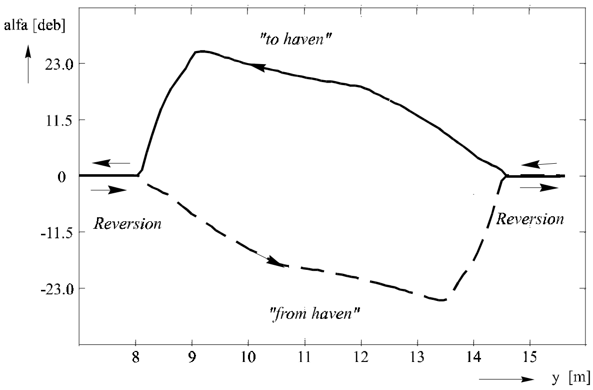

Fig. 6 Dig angle for a unloading traverse obtained using Fuzzy-Logic.

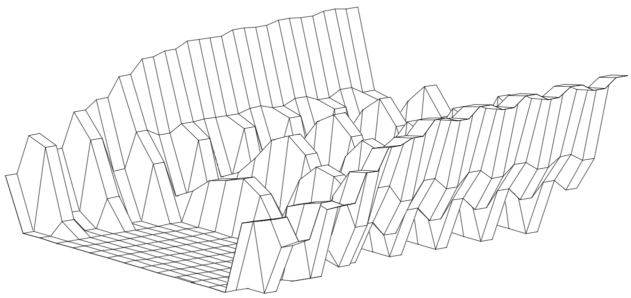

Fig. 7 Resulting end coal surface without complementary traverses. Dig angle obtained using by Fuzzy-Logic.

This result will be now compared with a numerical method, the dynamic programming approach.

5.2 Dynamic programming trajectory generation

A uniquely defined unloading trajectory also results, when fixing the start and goal surfaces, so that no rest hills remain. From Fuzzy approaches it is known that the effect of mechanical restrictions is reduced by using complementary traverses. Complementary layers are then interpolated between start coal surface and ship floor. This approach fixes the degree of freedom by finding optimal intermediate surface with the aid of the dynamic programming technique, starting from predefined start and target surfaces. Thus in each traverse, the position of the dig head and its elevation angle α must conform with the pre-computed dig heigth.

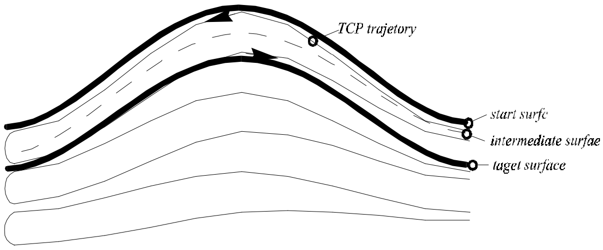

Fig. 8 Axial view of a complementary traverse strategy.

Bellman proposed an optimization procedure known as "dynamic programming" [Bellman-Kalaba, 1965], which is well suited for discretisable optimization problems with boundary conditions. The idea is here to systematically inspect all possible trajectories (in a discretized space) connecting start and target TCP. The best trajectory is determined in a local search using a multistage decision process. The systematization of the search is based on following principle (Bellman optimality principle):

The complete strategy will only be optimal, when each rest strategy is optimal, independently from which intermediate state it will be considered.

The application of this optimality principle leads to a backward search of the solution, from the target to the start point. In this manner all trajectories that should be considered can be evaluated. For arbitrary points during the search process it can be decided with local optimization criteria which trajectories will be further examinated and which ones can be eliminated.

As a result of preliminary studies [Bauchspiess, 1995], we will consider the unloading with two complementary traverses. In this paper the optimization will be used to obtain the shape of the efficient intermediate surface of a complementary layer unloading. Start and resulting surface are given and the optimization objective is to find the intermediate surface so that a given cost function is minimized

To obtain the intermediate surface the area between start and resulting surface will be quantized in a grid with N_i points between start and target TCP. The reversion process will be considered by a proper choice of the start and target configuration of the redundant manipulator, i.e., the elevation angle of the dig head must be zero at these points.

In the vertical direction a quantization with N_j points between start and target surface will be used. The main advantage of the dynamic programming approach is now evident: the boundary conditions, complicating most analytical methods, here bring a significant reduction of the search space.

A determined shape of the intermediate surface, characterized by the path from $P_{i,j}$ to $P_{i+1,k}$ has an associated cost, i.e., the coal removal cost in this particular point (forward and backward traverse) can be evaluated analytically. For the optimal shape of the intermediate surface from $P_{i,j}$ to the target, the sum of the individual costs will be a minimum. This minimum value is defined as the value of the criterion for that point. To find the optimal trajectory with Bellmans principle we must store successive values that will be used in the decision process (the so called multistage decision). The path can be locally stored as a direction vector: each point stores only the path information needed to find the next optimal point, as illustrated in **Fig. 9**.

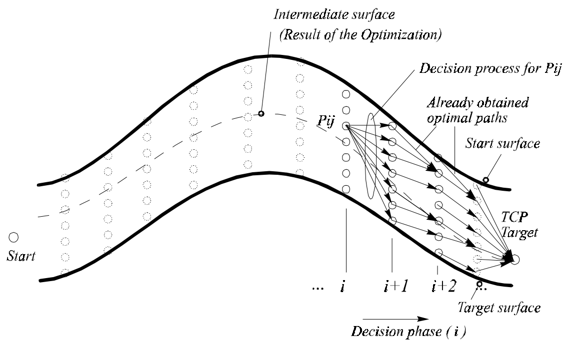

Fig. 9 Use of the dynamic programming for the optimization of the complementary layer unloading.

Each point in the quantized space will also be associated with a criterion value and a direction vector. These can be interpreted in the following way: Once one reaches point Pi,j, there will be only one optimal way to the target (given by the stored direction vectors), and it will be traveled with the cost value associated with $P_{i,j}$. So the quantized search space leads to a path-network; each registered path is a optimal path.

Using Bellmans principle the systematic generation of the path network can be formulated:

For all paths, that in phase i can lead from point $P_{i,j}$ to a point in phase i+1, i.e. to points $P_{i+1,k}$, k=1,N_j, we will evaluate the local path costs. The minimal sum of the path costs from $P_{i,j}$ to P_{i+1,k^*}, and the criteria value of P_{i+1,k^*}, characterize the optimal trajectory from $P_{i,j}$ to the target TCP point, and will be stored as the criteria value of $P_{i,j}$. The value k will be stored as the trajectory direction from $P_{i,j}$ to phase i+1.*

For the double complementary layer unloading the intermediate surface is obtained after the removal of the first layer. This implies that by the second (back) traverse, no degree of freedom is available; i must be so removed that the target surface results. This interrelation is shown in Fig. 10. The crosses indicate a point in the quantized search space. The criteria value must also consider a common evaluation in this point for forward and back traversing.

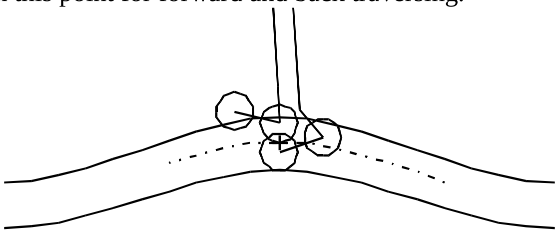

Fig. 10 Participation of both traverse directions in the complementary unloading approach, illustrating their contribution to the cost function for three positions of the intermediate surface.

So we need only to establish the cost function to obtain the optimal trajectory. In many optimization problems weighted sums of conflicting objectives are used. In this work the following objectives were used:

- *A good hit in the gorge; i.e. a configuration will be chosen that gives the smallest* γ.

- *A short intermediate surface length, to reduce energy consumption.*

- *Equality in the volumes carried by the forward and backward traverses.*

In our approach variations in the layer height must be compensated by traverse velocity adjustments.

Mathematically the evaluation of o path that connects points Pi,j=(x,y) and Pi+1,k=(x_{zw},y_{zw}) can be given by:

Cost for $P_{i,j} \Rightarrow P_{i+1,k}$:

$$V_{zw} = r_1\gamma_V^2 + r_2\gamma_R^2 + r_3\gamma_{Va}^2 + r_4\gamma_{Ra}^2 + r_5H_{zw}^2 + r_6H_{zwa}^2 + r_7((x_{zw} - x_{zwa})^2 + (y_{zw} - y_{zwa})^2) \quad (2)$$

The indices $_V$ and $_R$ stand for forward and back traverse, so that γ_V and γ_R describe the hit angle for the forward and the back traverse in the position (x_{zw},y_{zw}).

The result of the optimization is presented in **Fig. 11**, for the given weighting factors. In this figure we recognize a similarity with the trajectory obtained using the Fuzzy Logic approach, which gives a smaller dig angle at the start and a greater value towards the end of the traverse.

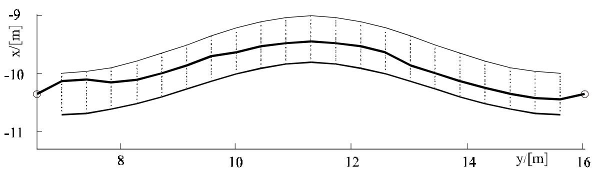

Fig. 11 Optimized trajectory obtained using Bellman's principle for the complementary layer approach. Weighting factors: r1=r2=r3=r4=1, r5=r6=0.01, r7=1.

There the dig angle was established in a heuristically given rule basis. Here we used an analytical method, but we must point out that the choice of the weighting factors is also a more or less heuristically procedure. So by no means one can categorically say that in all cases the dynamic programming with its greater computational efforts will give the better trajectory planning. It is the best for the given cost function, but who can give us the ultimate cost function?

The proposed technique can be expanded to consider a global axial optimization, as shown in [Bauchspiess, 1995].

6. Experimental Results

Digital processing equipment permits actually the control of complex tasks e.g. hydraulic driven manipulators in such a precision as demanded by the manufacturing industry. These, which for long time were considered as "very difficult" to be controlled because of their extremely non-linear characteristics, have newly attracted research interest.

To verify the theoretical results a hydraulic manipulator guided by a CCD-video camera was used [Bauchspiess, 1995], Fig. 13**.** The main components of the experimental assembly are depicted schematically in Fig. 13**.**

To implement a non-linear decoupling controller a DSP32C digital signal processor in a PC-486 host was used. The image interpretation and a predictive servocontrol was carried out by another PC-486 with a DSP16A and a DSP32C.

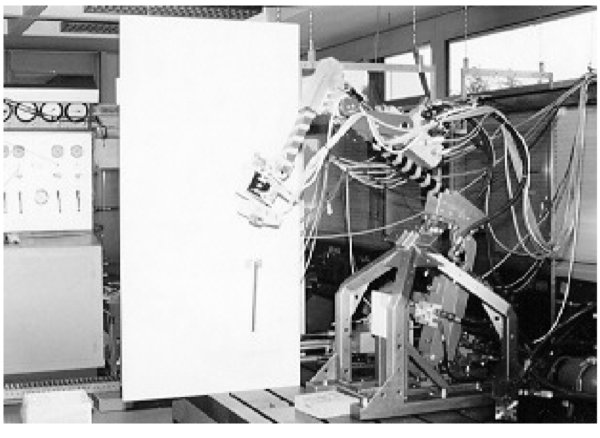

Fig. 12 Hydraulic manipulator guided by a CCD-camera.

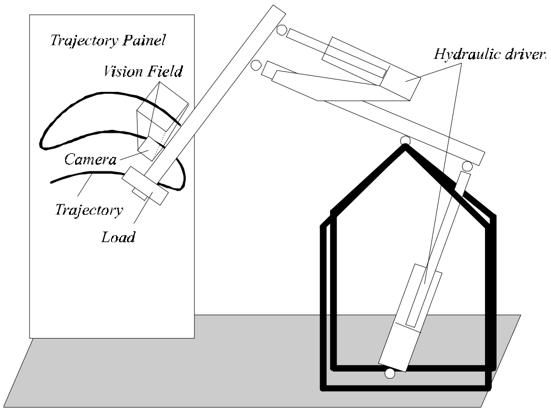

Fig. 13 Schematic view of the hydraulic manipulator.

The unloading trajectory tracking (of the optimized trajectory obtained before) is shown below. The corresponding joint angles and error values are shown in Fig. 15**.** A good tracking performance is observed, only in points of greater trajectory discontinuity a error greater than 2 mm is registered.

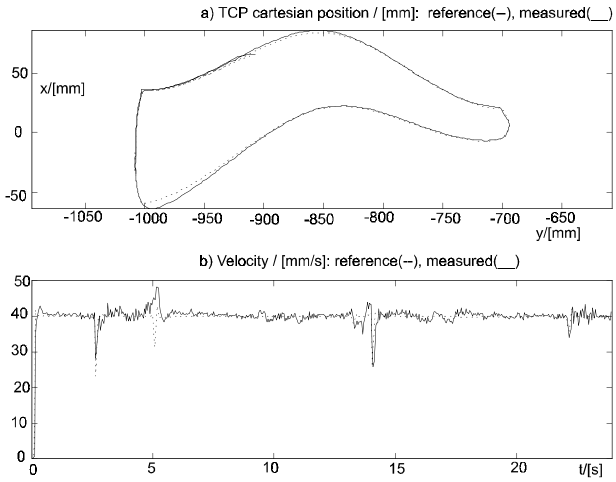

Fig. 14 Sensor guided trajectory tracking for the spline interpolated coal unloading trajectory.
Sampling period: T = 10 *ms*, Velocity: v_{ref} = 40 *mm/s*.

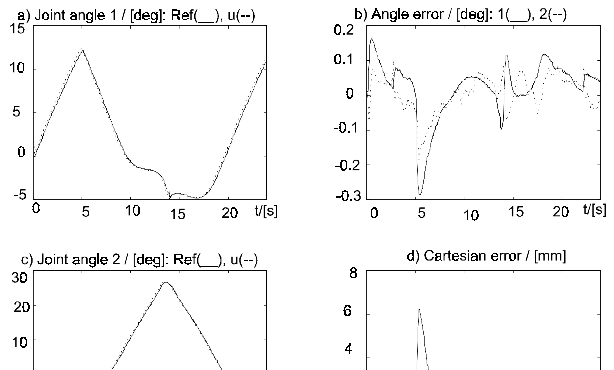

Fig. 15 Joint angle and error relatives to Fig 14.

7. Conclusion

Main aspects of the automatic path generation for a redundant coal unloader were examined in this paper. Two techniques were used to optimize the sensor guided unloading process. It was shown that the trajectory obtained by dynamic programming resembles that obtained by the fuzzy logic approach.

Considering the heuristically manner of establishing weight factors in the dynamic programming it can not be said that the result will be necessarily better than that obtained by fuzzy evaluation of rules obtained from the expertize of a crane operator. The Fuzzy Logic approach seems to be better suited for industrial applications, since it can better cope with new situations (simple adding new rules to the existing rule base). Thus, it is, in fact, an *expandable variable structure controller*, easily designed based on expert knowledge and experimental practice.

The implementation of a predictive servocontroller on a CCD-guided hydraulic robot demonstrates that the obtained trajectories are feasible. The dynamic tracking error, a crucial factor to guarantee quality in automated robot guiding, is very small. The residual error observed in the measures are mainly due the friction in the hydraulic cylinders. This is a matter of technological restriction of this kind of drives and demands constructive issues to reduce their influence.

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