A Human - machine interface for teleoperation of arm manipulators in a complex environment

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Abstract

This paper discusses the feasibility of using configuration space (C-space) as a means of visualization and control in operator-guided real-time motion of a robot arm manipulator. The motivation is to improve performance of the human operator in tasks involving the manipulator motion in an environment with obstacles. Unlike some other motion planning tasks, operators are known to make expensive mistakes in such tasks, even in a simpler two-dimensional case. They have difficulty learning better procedures and their performance improves very little with practice. Using an example of a two-dimensional arm manipulator, we show that translating the problem into C-space improves the operator performance rather remarkably, on the order of magnitude compared to the usual work space control. An interface that makes the transfer possible is described, and an example of its use in a virtual environment is shown.

1 Introduction

The goal in this project is to improve the performance of human operators in tasks that involve motion planning and control of complex objects in environments with obstacles. The human performance in such tasks is known to be patently inferior. Our focus is on developing a visual computer interface that would allow the operator to visualize and perform the work in the task configuration space (C-space) rather than in the work space (W-space) as usually done. To make it feasible, a computer intelligence is provided that works alongside with human intelligence in real time. To this effect, we combine the “desirable” features of human and machine intelligence and exploit their individual strengths. This area belongs to the field of human-centered systems, which has seen growing interest in recent years. The intent of this work is to be applicable to many existing research [1] and commercial problems [2, 3].

There is a large and rapidly developing class of technical systems that are dependent on human contribution for their operation. In various teleoperated systems (such as in space,
nuclear reactors, chemical cleanup sites, underwater probes) human operators plan and
guide the motion of remotely situated devices through interaction with computer displays
or three-dimensional models of the device. Familiar examples include control of the NASA
Shuttle arm and of the Titanic exploration probe. In such tasks operators are known to
make mistakes of overlooking collisions with surrounding objects; this results in expensive
repairs and limits the system effectiveness. People seem to be unable to navigate and
manipulate remote equipment without colliding with objects in the environment.

Similar problems occur in other settings. Guiding the position of a robotic welding gun
or spray painting device with a simultaneous translation and orientation adjustment seems
to be particularly difficult for people, even when visual feedback is provided. Performance
is very poor in a variety of these movement planning tasks when time is not a constraint
(the Shuttle arm, for example); it becomes progressively worse in real-time operation, in
three-dimensional (3D) vs 2D tasks, and when system dynamics are involved (masses,
inertia etc.). (Underwater exploration probes, for example, cannot stop while the operator
considers the next move).

Experiments with human subjects [4, 5] suggest that the problem is in the peculiarities
of human spatial reasoning: humans have difficulty handling simultaneous interaction with
objects at multiple points of the device’s body, or motion that involves mechanical joints
(such as in arm manipulators), or dynamic tasks. Learning and practice improve the per-
formance rather little. Furthermore, the performance pattern is the same when operating
a physical rig or performing the task on a computer screen and moving the arm links with
a mouse (see more on this in Section 5).

On the other hand, these experiments confirm the expected fact that in a maze-searching
problem, if information is provided about the whole maze (a bird’s-eye view), human per-
formance is well above the fastest computer with the best known algorithms [6]. Figure
1 gives an example of human performance in a maze: after inspecting the maze for a few
seconds, the subjects grasp the problem and produce an almost optimal path from point
S to point T. This contrast in the subjects’ performance in the two tasks above poses a
question as to whether a human-machine interface, perhaps with adequate machine intelli-
gence, can be developed to improve human performance is such applications. The current
work is an attempt to answer this question. The system we chose to model the problem is
a two-dimensional (2D) revolute-revolute (RR) arm manipulator operating in an environ-
ment with unknown stationary obstacles (see Figure 2). The arm has two links moving in
a plane, and two revolute joints (degrees of freedom). The idea it to present the problem
to the human as one of moving a point in a maze (a task that humans are good at) rather
than the actual problem of moving a jointed kinematic structure (which humans are not
good at). We exploit the fact that for today’s computer algorithms, which are based on
spatial geometry and topology tools, both tasks present essentially the same maze-searching
problem [7]. By transforming the problem to the arm configuration space (C-space), the
arm is shrunk to a point in the space of its control variables.

Below, the properties of work space control are discussed in Section 2, and those of the
configuration space – in Section 3. The proposed interface is then presented in Section 4.
Figure 1: Human performance in a maze.

followed by some experimental results in Section 3 and discussion in Section 5.2.

2 Work Space Control

The revolute-revolute (RR) planar arm considered is as follows, Figure 2: Joint $J_1$ (the shoulder) is attached to the floor, and is the origin of a fixed reference system. Joint $J_2$ (the elbow) connects the two links, $l_1$ and $l_2$. The Cartesian coordinates of the endpoint (point P) are $(x, y)$. Moving the arm involves changing the joint angles $\theta_1$ and $\theta_2$. There are fixed obstacles in the arm environment ($O_1$ and $O_2$, Figure 2). There are no constraints on the shape of the obstacles or the arm links. The task is to move the arm from a position S (Start) to the position T (Target), Figure 3.
2.1 Motion Control in W-space

Arm motion is controlled with the computer mouse, in two separate modes - joint-mode and tip-mode [4]. The former allows control of individual joints by positioning the pointer closer to one of the joints and pressing the left mouse button, which causes the selected joint to move and align with the pointer. The tip-mode allows control of the endpoint through the use of the middle mouse button; computer software then calculates the corresponding joint angles of the links and positions them accordingly.

In the joint-mode, the algorithm computes a unit vector which describes the straight-line direction from current configuration to specified target configuration. Assuming the configuration does not violate step constraints (if the distance to it is larger than the configured step size, a new target is computed by multiplying the direction vector by step size), the new configuration becomes the specified configuration. In tip-mode, the direction vector describes the new position of the arm endpoint (again, subject to step constraints), and so one needs to recover the new arm configuration from the endpoint position \((x, y)\). This is done via the inverse kinematics equations:

\[
\theta_2 = \arccos\left(\frac{x^2 + y^2 - l_1^2 - l_2^2}{2l_1l_2}\right) \tag{1}
\]

\[
\theta_1 = \arctan\left(\frac{y}{x}\right) - \arctan\left(\frac{l_2 \sin \theta_2}{l_1 + l_2 \cos \theta_2}\right) \tag{2}
\]

The current arm configuration is used to resolve multiple solutions that are given by the inverse kinematics. The final step in either motion mode is to determine if the new configuration would place the arm in contact with the obstacle and, if so, disallow the movement.
and wait for further operator input. Figure 4 shows an example of average human performance in W-space motion control; the dotted line is the trajectory of the arm endpoint along the way from S to T. The path length is the integral of changes in both joint angles along the way.

2.2 Characteristics of the Work Space Control

Aside from being the traditional method used, W-space control has some desirable properties:

- Interaction with the physical arm and its environment makes it easier for the operator to visualize the global navigation, such as to determine the next target configuration based on some scene property; e.g. the operator may decide to move the arm such that its left side will be in proximity of some object.

- If the obstacles layout is not of much constraint on the arm motion, this approach can yield very good (near optimal in terms of path length and time taken) results.
Figure 4: An example of average human performance in W-space motion control.

- Given the familiar physical layout, it may be easier for the operator to benefit from memorization of motion and improve with training.

However, this type of control also has some serious drawbacks which may outweigh its positive sides:

- In tip-mode, calculating the inverse kinematics becomes progressively more complex and time-consuming as the number of joints increases.

- In a complex environment, the operator may have hard time determining which direction of local motion is better, or whether a given direction leads to a “dead-end”. This is a serious drawback: for example, in Figure 4 one can pass obstacle $O_3$ with the elbow to the left or to the right; one of those turns out to be wrong as it leads to a dead end, and this would become clear only significantly later.

- From the standpoint of motion planning, a complex environment is not necessarily one with many or with large obstacles; this is much clearer in C-space (see Section 3) than in W-space.
Consequently, W-space control is likely to produce redundant motion: as illustrated in Figure 4, the operator will often try, backtrack, try again, backtrack again, and so on until the passage is found, not rarely through blind luck. This also endangers the arm, as all such motion multiplies potential collisions with surrounding objects. While most people do benefit from a training period in such systems, the training can be costly (in terms of equipment use and damage inflicted on the arm) and time consuming.

3 Configuration Space Control

The arm is the same 2D RR arm manipulator described in Section 2 (Figure 2). Assume that the arm is capable of gathering information about the objects in its environment via its sensors. To simplify the discussion, assume that those are tactile sensors - i.e. the arm can detect an obstacle when it comes in contact with one. The human operator can of course view the entire workspace, Figure 3. The task is as before - to move the arm from position S to position T in the arm’s work space.

The arm can be defined in terms of the shoulder angle $\theta_1$ and the elbow angle $\theta_2$. The set of all configurations $(\theta_1, \theta_2)$ define the arm’s configuration space (C-space), which can be represented as the surface of a common two-torus. An arm configuration in W-space corresponds to a point in C-space. This mapping preserves continuity; small change in W-space position corresponds to a small change in the C-space position. A geodesic line between two points on the torus (a straight line in the plane $(\theta_1, \theta_2)$) is the “shortest path” between the points: four such paths can actually appear [6].

3.1 Motion Control in C-space

We will now attempt to control the arm motion indirectly, via its point image in C-space (C-point). Each time the operator moves the C-point slightly, the algorithm recovers a new set of configuration variables $(\theta_1, \theta_2)$ from the C-point coordinates and automatically translates it into the actual motion in W-space. That is, after the direction vector is calculated and step size is taken into account, similar to the joint-mode in W-space control, angles $\theta_1$ and $\theta_2$ become available, and they are used to control the arm’s next step. Though not necessary for control purposes, for convenience a W-space window with the arm real-time motion is shown next to the C-space window used by the operator.

Recall that the Cartesian position $(x, y)$ of the arm endpoint is the tip-mode parameter in W-space control. Certain applications, e.g. grasping, may require knowledge of this parameter. If necessary, $(x, y)$ values can be recovered from C-space information via the direct kinematics equations:

$$x = l_1 \cos \theta_1 + l_2 \cos(\theta_1 + \theta_2)$$  \hspace{1cm} (3)

$$y = l_1 \sin \theta_1 + l_2 \sin(\theta_1 + \theta_2)$$  \hspace{1cm} (4)
We are now one step away from converting the complex problem of W-space control to a simpler problem of navigating a point in the maze (C-space). What is missing is the maze itself. This is done by computing the C-space obstacles, also called virtual obstacles. Each point of a virtual obstacle corresponds to an arm configuration that is not attainable because of interference with the corresponding physical obstacle. The related \((x, y)\) positions in W-space may or may not be occupied by an obstacle - in the latter case such pieces of an obstacle are called its shadows. A finite number of obstacles in W-space produce a finite set of virtual obstacles in C-space. The boundaries of virtual obstacles are known to consist of simple closed curves \[6\]. Since virtual obstacles are defined in terms of arm variables \((\theta_1, \theta_2)\), their shape is visually unrelated to the shape of the W-space obstacles \[7, 8\].

### 3.2 Construction of C-space Obstacles

The greatest improvement in the operator performance comes when full information (the bird’s-eye view) about C-space is available (on the issue of operating with uncertainty, see the discussion in Section 5.2). We thus need to compute and display all the virtual obstacles. An intuitive approach proposed in \[8\] is to treat each link separately. First, link \(l_2\) is ignored, and all free space points for the whole range of values \(\theta_1\) are computed. Points of the arm contact with physical (W-space) obstacles are recorded and become part of the corresponding virtual obstacle. Then, for each value of \(\theta_1\) within its appropriately digitized range, free space points for the whole range of values \(\theta_2\) are computed in the same fashion, by rotating link \(l_2\) around positions of joint 2 determined by the current value \(\theta_1\). Depending on the representation chosen for the virtual obstacles, their “insides” may have to be filled using a polygon-filling algorithm.

For the two-dimensional problem in question, C-obstacle calculation can be greatly simplified by tracing the obstacle boundaries with arm links and thus immediately creating their C-space images. Note that two or more W-space obstacles can produce a single virtual obstacle; that is, for the purposes of motion control, they would indeed be one obstacle. Our simulation uses an efficient variation of this procedure \[7\], which makes use of the Bug1 \[6\] algorithm.

In brief, procedure Bug1 operates as follows: the point robot starts moving along the straight line towards target point T. If it encounters an obstacle, a hit point H is defined at the encounter location, and the robot turns and moves in a prespecified direction (say, left) along the obstacle boundary. Once the obstacle is circled, and H is once again encountered, a leave point L is defined on the obstacle, which is the point closest to T. The robot then takes the shortest path to L and then proceeds to T in straight-line fashion, repeating the procedure whenever an obstacle is encountered. The procedure converges to T or informs that this is impossible if true. The algorithm’s computational complexity is linear in the perimeters of the W-obstacles.

Figure \[3\] gives the C-space representation of W-space of Figure \[3\]. Angle \(\theta_1\) is along the horizontal axis, \(\theta_2\) - along the vertical axis. The range of change of each angle is \(2\pi\), making C-space a square. The dark areas represent the virtual obstacles. The C-space
correspondence to a two-torus means in that all four corners of the square are identified (i.e., correspond to the same point). Similarly, the top and bottom edges of the square are identified, and so are the left and right edges. Given this last fact, note that the C-space in Figure 5 contains only one virtual obstacle which corresponds to four physical obstacles in W-space, Figure 4. Point T is chosen as the corner point of the C-space square; in principle, therefore, one’s moving from point S to any corner will produce a legitimate (if not necessarily the shortest) path for the arm in W-space.

3.3 Characteristics of the Configuration Space Control

This mode of control has several distinct advantages (see also Results, Section 3):

- From the operator standpoint, the task is simplified greatly: instead of dealing with a complex jointed kinematic structure, the operator has to solve a simple maze-
searching problem with complete information, which humans are very good at.

- One explanation for the task simplification is that the responsibilities are divided in this mode - the operator can think of the motion planning only, while the computer takes on the problem of collision analysis.

- The arm’s actual motion is quickly and easily calculable from user input, guaranteeing good real-time performance.

- Unlike in W-space, performance here does not seem to depend much on the obstacle layout. Indeed, this mode has consistently yielded near optimal performances by the human operator in a variety of settings. This is consistent with the fact that humans can easily “see” the path in a bird-eye view of a fairly complex maze, while they have difficulty visualizing a path in a simple scene with an arm manipulator (see Figure 3). The operator easily discards many “dead-end” directions in the maze representation, but find it difficult to identify them in Figure 3.

- The mode requires very little training, mostly to get used to the peculiarities of flat presentation of two-torus - e.g. to the fact that once the point reaches the top edge of the C-space square, it appears at the bottom edge. In fact, performance has been just as good for an inexperienced user as for an experienced one.

- Unlike the W-space control, the subject can often easily see if a solution (a path) exists. In fact, it is this kind of decision-making that the operator uses extensively along the way to discard potential dead-ends.

A few drawbacks deserve to be noted of this mode, although their impact is not nearly as great as those in W-space control:

- The fact of dealing with an abstract (C-) rather than physical (W-) space may make it difficult for the operator to address some global navigation tasks, such as choosing targets for the arm to reach. This problem is easily avoided if the corresponding W-space view is drawn in parallel with the C-space used by the operator (see Figures 3 and 4).

- While extremely helpful in 2D, the mode is not likely to easily generalize to more complex multi-link systems see discussion in Section 5.2).

- Computation of C-space is an expensive operation which must be performed to satisfy the complete information model (see Section 5.2 for details on the proposed uncertainty model).

4 The Interface

The current version of the user interface has several interesting features:
• The user can generate - e.g., for practice - custom or random obstacle environments around the arm.

• Both C-space and W-space displays are provided. As mentioned above, the W-space window is a good tool for visualizing global navigation tasks, such as deciding on a target position for the arm endpoint. The user can, for example, define the target in terms of the arm endpoint Cartesian coordinates \((x, y)\), and the computer will recover the corresponding arm configuration through inverse kinematic equations (1, 2).

• Motion control in C-space is done via mouse interaction; joystick control is being considered, especially in the future 3D extension.

• For experimental purposes, the user can switch back and forth between C-space and W-space control.

• The simulation keeps track of the time elapsed and path traversed, to help compare the two control methods.

5 Results and Discussion

5.1 Results

Overall, the proposed C-space control mode performed admirably when compared to the traditional W-space control. Current results (achieved with a C-space interface version that is still under development) show improvement in performance on the order of magnitude when switching from W-space control to the proposed C-space control. The path produced approaches the optimal (shortest) path and time to complete the task. Further, the cognitive part of the time spent in the case considered is negligible, since the 2D mazes produced by the virtual obstacles are simple to navigate and to learn. This remarkable fact puts the human operator ahead of the existing computer algorithms, contrary to the W-space control where human performance has been much worse. It also suggests interesting questions and extensions to more difficult 3D cases.

Table 1 summarizes information from a series of controlled experiments performed in 1996-97 at the UW Robotics Lab, to test human performance in motion planning tasks. One of the tasks given to the human subjects was to move a two-link arm, very similar to the one considered in this paper, from the start to target configurations. Only W-space control was available (Section 2). In the table, the path length is the integral of both joint angle changes during the motion; also given is the time ((in seconds) taken by subjects to complete the task. The data given represents the performance of 12 subjects on the second day of tests, after training and practice on the previous day. (The results on 48 untrained subjects, in tests with a simulated as well as physical arm manipulator, were quite similar). A full analysis of this work can be found in [5].
Table 1: Descriptive Statistics

| Variable    | Mean  | Minimum | Maximum | Stand. Dev |
|-------------|-------|---------|---------|------------|
| path length | 129.04| 15.13   | 393.90  | 107.99     |
| time        | 504.83| 90.00   | 900.00  | 365.89     |

No similar study was carried out for the C-space control mode. However, based on the observations and tests by these authors, the study is not necessary: the performance improvement is very clear and consistent. Further, it is clear that in the task of Figure 3 different subjects are likely to produce almost the same (nearly optimal) path, with the mean path length of about 12, the standard deviation of about zero, and the mean time below 1 min. The path length and time values in Table 2 show an order of magnitude improvement compared to the data on W-space control in Table 1. Sample results from 5 consecutive runs of C-space control are given in Table 2. One of these runs is shown in Figures 5 and 6.

Table 2: Sample Runs

| Variable    | Run 1 | Run 2 | Run 3 | Run 4 | Run 5 |
|-------------|------|------|------|------|------|
| path length | 12.67| 12.39| 12.24| 12.27| 12.28|
| time        | 56   | 54   | 53   | 53   | 54   |

The consistency between these runs - both in path length and completion time - is very similar to the subjects' performance in a common maze-searching problem. It also stands in contrast to the wide range of results produced in the W-space model. This suggests that the proposed transformation to C-space control does indeed make the task at hand similar to the maze-searching task.

5.2 Discussion

This paper proposes an approach to human-guided teleoperation of a robot arm manipulator based on the configuration space (C-space) rather than on the common work space (W-space) control. Instead of directly confronting the problem of collision analysis, which is known to be extremely challenging for the human spatial reasoning, the task is offered to the operator in C-space where one can concentrate on global navigation, leaving collision analysis to the computer. Thus reduced task becomes a maze-searching problem in which humans are known to be very good. Designing such a system takes, first, calculation of the C-space, and second, an adequate user interface.

While this approach can be immediately useful even in its two-dimensional version described, in order to become a truly universal tool it needs to be extended to the three-dimensional case and to more degrees of freedom. The advantage for the operator of dealing with a point rather than a complex jointed kinematic structure is obvious. The challenge is to produce an adequate user interface (specifically, develop ways of visualizing and guiding
Figure 6: The sample task of Fig. 3: C-space motion control. The corresponding W-space in Fig. 7.

a point in a higher-dimensional space) and to do C-space calculation and collision analysis fast enough to keep the operator active at the control station. One possibility here is to help the operator handle the environment with incomplete, rather than complete, information; this would mean a significant reduction in the C-space computation costs. Success in this area will also mean applicability of the approach to a dynamic environment with moving obstacles. Computer algorithms for motion planning with incomplete information are available (e.g. [6]). Experiments with human subjects operating in an unknown maze [4, 5] suggest that humans might be able to handle this case as well.

The immediate problem is to determine if the resulting three dimensional C-space will still be as helpful to the human in performing the task as the two dimensional case was. Also necessary will be: algorithms for computing C-space for a multi-link arm; algorithms for collision analysis in 3D space; procedures for C-space visualization, and for arm motion control in W-space. These are likely to raise issues of computational complexity and real-time control.
Figure 7: The W-space view of the task in Fig. 6. The path produced does not contain unnecessary “detours” common to W-space control (see Fig 4), and approaches optimal path for this task.

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