TELEMANIPULATION: THE VIRTUAL TOOL APPROACH AND ITS INTERVAL-BASED JUSTIFICATION

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I. FORMULATION OF THE PROBLEM: TELEMANIPULATOR INACCURACY

Telemanipulators Are Needed

In many real-life mechanical tasks, it is difficult or even impossible to use humans:

- Some environments are too dangerous for a human being: for example, when we manipulate objects in space, inside a radioactive part of a nuclear reactor, in a dangerous chemical environment, or even in a potentially dangerous environment such as handling viruses that cause deadly diseases.
- In other environments, there is no danger to the human operator, but there is a significant risk of contamination of the object: e.g., in handling microchips, lunar samples, etc.

In all these cases, reasonably simple mechanical tasks can be done by an automatic mechanical hand-arm. However, there is a limit on the complexity of the tasks that automatic devices can do. For more complicated tasks, for which we cannot use a completely automated system, we must use *telemanipulators*, i.e., devices in which a mechanical hand-arm copies the movements of a human operator.

Telemanipulators: Successes

The main goal of the telemanipulator is to reproduce the operator's movements as accurately as possible.

A human hand is a very flexible instrument. In mechanical terms, we can say that it has many degrees of freedom: we can move and rotate the hand itself, the arm, each finger, parts of each finger, etc. Thus, to reproduce its movements accurately, the manipulator also has to have many degrees of freedom.

At present, the best of widely available hand-arm manipulators, the Utah/MIT hand, has 22 degrees of freedom. It is still slightly less than a human hand, because, e.g., it only has 4 fingers and not 5. However, it can perform many important tasks that a human hand can do.

This hand was not designed for telemanipulation only. It has many other applications: e.g., it can even twist itself into the positions that would have been impossible for a human hand.

Telemanipulators: Problems

Both in the Hollywood movies and in the self-made movies that researchers show at robotic conferences, telemanipulation works perfectly well: a robotic hand exactly reproduces the operator's movements. This is indeed happening in many application areas, but this reproduction accuracy is extremely difficult to achieve.

If we simply measure the pressure, etc., applied by the operator's arm, and send exactly proportional control signal to the electric motors that control different degrees of freedom of the robotic arm, we get a behavior that is often drastically different from what the operator did. For example, the operator's firm grip on the object may be distorted into the robotic arm dropping it, and vice versa, the operator's tender approach to a fragile object may result in a robotic arm's bumping into the actual object and damaging it.

There are three main reasons for the difference between the movements of the human and robotic hands:

- first, the sensors that measure the human hand's pressure are not 100% accurate;
- second, the motors and actuators are not perfect, and do not react precisely to the commands;
- third, the mechanical characteristics of the robotic hand itself are somewhat different from the mechanical characteristics of the operator's hand.

As Manipulators Get More Complicated, These Problems Get More And More Important

The above inaccuracy problems can be traced even on the example of simple manipulators that have a few degrees of freedom, but for more advanced manipulators, these problems become more and more acute. Indeed, for a manipulator, more advanced means that this manipulator has more degrees of freedom. Each degree of freedom bring its own inaccuracy, so if we have 22 degrees of freedom, then in principle, we get 22 sources of inaccuracy all leading to the huge inaccuracy of the resulting action.

Let us give a simple example.

- If we have a 3-finger manipulator, then for this manipulator to grip an object, it must place one finger below it, and two fingers above it. Due to inaccuracy, we may have a slightly distorted position, but we will still keep firmly 3 points on the object.
- For a 4-finger arm that is similar to the human arm, we need to place 3 fingers on top of the object. If, e.g., the upper surface is planar, we must have all 3 fingers on one line. Due to inaccuracy, one of these fingers may be higher than the others. As a result, this finger may not contact the object at all, and hence, the grip will not be as firm as we desired.

So inaccuracy is harmful. In order to figure out how to decrease this inaccuracy, let us first analyze how we can describe it in precise terms.

II. MATHEMATICAL DESCRIPTION OF THE PROBLEM: ENTER INTERVALS

Describing Inaccuracy: Intervals

For sensors and other measuring instruments, manufacturers usually give a guaranteed upper bound on the measurement error.

> Indeed, if no such bound is supplied, this means that the manufacturer does not guarantee any accuracy. So, if we get some value from this instrument, the actual value of the measured quantity can arbitrarily differ from this "measured" value. In other words, no matter what we "measure" by this instrument, we can still have an arbitrary actual value. In other words, if no upper bound is given, this "measurement" does not give us any information about the actual value, so there is not reason to call it a measurement at all.

In addition to the upper bound, we sometimes know the *probabilities* of different values of measurement error.

To get such probabilities, we need a lot of experimental data, which we usually, for manipulators, do not have.

So, for manipulators, the typical information about the measurement error consists simply of knowing its guaranteed upper bound Δ. So, if the measured value of some quantity is $\tilde{x}$, this means that the actual value x of the measured quantity is within the interval $[\tilde{x}-\Delta, \tilde{x}+\Delta]$ (and we cannot a priori exclude the possibility of x being equal to any of the real numbers from this interval).

Similarly, the errors caused by actuators can also be described by intervals. As a result, at every moment of time, we have the following situation:

- the teleoperator applies the control values $x_1, \ldots, x_n$;
- due to measurement errors, the telemanipulator system measures the values $\tilde{x}_1, \ldots, \tilde{x}_n$ that are, in general, different from the corresponding values x_i: $\tilde{x}_i = x_i + \Delta x_i$, where $\Delta x_i \neq 0$; the only information that we have about Δx_i is that $|\Delta x_i| \leq \Delta_i$ for some manufacturer-supplied accuracies $\Delta_1, \ldots, \Delta_n$.

III. HOW WE CAN CORRECT MANIPULATOR INACCURACY: THE IDEA OF VIRTUAL TOOLS

Main Idea

Although a human hand-arm has many degrees of freedom, we rarely use all of them in the same movement. Usually, the movement in different degrees of freedom is very much *coordinated.*

For example, if we have already firmly grasped an object, then we move the arm as a whole and, unless necessary, do not use the ability to move fingers and/or or fingertips separately.

There is a limited number of typical movements of this type, and a teleoperator can pretty well describe which of these typical movements he is applying at any given moment of time. When we get this information, we can use it to set up a similar coordination between the degrees of freedom of the robotic hand-arm. When the resulting constraints are in place, the originally flexible robotic hand acts as a new tool that is specifically designed for this type of movement. Since in reality, we are still using the same robotic hand, this is not a new *physical* tool, but a *virtual* tool.

We will see that using virtual tools can indeed be very helpful.

How to Describe Movement Type in Precise Terms

In precise terms, a fixed movement type means that we cannot have *arbitrary* values of $x_1, \ldots, x_n$: these values must satisfy one or several restrictions (constraints).

> For example, if we want the arm to move as a whole, then one of these constraints may take the form $x_1 = x_2$ (or $x_1 - x_2 = 0$), where x_1 and x_2 are pressures applied by two fingers. If we want to preserve the distance between the two fingertips, then we may require something like $(x_1 - x_2)^2 + (x_3 - x_4)^2 - \text{const} = 0$.

In general, we have one or several constraints of the type $F(x_1, \ldots, x_n) = 0$.

So, for the actual values $x_i = \tilde{x}_i - \Delta x_i$, in addition to the intervals $[\tilde{x}_i - \Delta_i, \tilde{x}_i + \Delta_i]$ of possible values, we have the additional constraints of the type

$$F(x_1, \ldots, x_n) = F(\tilde{x}_1 - \Delta x_1, \ldots, \tilde{x}_n - \Delta x_n) = 0.$$

Since inaccuracies Δx_i are small, we can expand the function F in Taylor series and ignore terms that are quadratic or of higher order in Δx_i. As a result, each original constraint $F_k(x_1, \ldots, x_n) = 0$ becomes a *linear* constraint on possible values of Δx_i:

$$F_{k1} \cdot \Delta x_1 + \ldots + F_{kn} \cdot \Delta x_n - F_k = 0, \qquad (1)$$

where

$$F_{ki} = \frac{\partial F_k(x_1, \ldots, x_n)}{\partial x_i}_{|x_1 = \tilde{x}_1, \ldots, x_n = \tilde{x}_n}$$

and $F_k = F_k(\tilde{x}_1, \ldots, \tilde{x}_n)$.

How to Use the Movement Type to Decrease Uncertainty

If we know relations (1), then instead of the original intervals $[\tilde{x}_i - \Delta_i, \tilde{x}_i + \Delta_i]$, we may have *narrower* intervals

$$[\tilde{x}_i - \underline{\Delta}_i, \tilde{x}_i + \overline{\Delta}_i],$$

where $\underline{\Delta}_i$ is the solution to the minimization problem

$$\Delta x_i \to \min$$

under the conditions

$$-\Delta_j \le \Delta x_j \le \Delta_j, \ 1 \le j \le n;$$

$$F_{k1} \cdot \Delta x_1 + \ldots + F_{kn} \cdot \Delta x_n - F_k = 0, \ 1 \le k \le K,$$

and $\overline{\Delta}_i$ is the solution to the similar maximization problem

$$\Delta x_i \to \max$$

under the same constraints.

Both optimization problems are linear programming problems, and they can be easily solved by using the standard linear programming techniques.

Within these intervals, we select the control values that satisfy all required equalities.

A Simple Example Showing That Constraints Can Decrease Uncertainty

Suppose that we have a movement in which two fingers have to move in the exact same way, i.e., in which $x_1 = x_2$. Suppose that the actual movement was $x_1 = x_2 = 1$. Let us also suppose that the measurement accuracy is $\Delta_1 = \Delta_2 = \Delta_3 = 0.2$. Due to measurement errors, we get, e.g., the following two sensor readings: $\tilde{x}_1 = 1.1$, $\tilde{x}_2 = 0.9$.

If we do not take the constraint into consideration, then we get intervals $[0.9, 1.3]$ for x_1 and $[0.7, 1.1]$ for x_2. For both variable, it is possible to have movement reproduction errors as high as 0.3.

If we do take the constraint $x_1 = x_2$ into consideration, then, as one can easily see, the possible values of $x_1 = x_2$ lie in the *intersection* of the two intervals: $[0.9, 1.3] \cap [0.7, 1.1] = [0.9, 1.1]$. For values from this intersection, the largest possible reproduction error is 0.1. In other words, in this simple example, we have a 3 times decrease in reproduction error.

Implementation

We have actually implemented several virtual tools for grasping and manipulation with the Utah/MIT hand. Ax a result, we do have an improved telemanipulation performance.

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