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# Force control: a bird's eye view

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**Abstract**

This paper summarizes the major conclusions of twenty years of research in robot force control, points out remaining problems, and introduces issues that need more attention. By looking at force control from a distance, a lot of common features among different control approaches are revealed; this allows us to put force control into a broader (e.g., differential-geometric) context. The paper starts with the basics of force control at an introductory level, by focusing at one or two degrees of freedom. Then the problems associated with the extension to the multidimensional case are described in a differential-geometric context. Finally, robustness and adaptive control are discussed.

## 1 Introduction

The purpose of force control could be quite diverse, such as applying a controlled force needed for a manufacturing process (e.g., deburing or grinding), pushing an external object using a controlled force, or dealing with geometric uncertainty by establishing controlled contacts (e.g., in assembly). This paper summarizes the major conclusions of twenty years of research in robot force control, points out remaining problems, and introduces issues that, in the authors' opinions, need more attention.

Rather than discussing details of individual force control implementations, the idea is to step back a little bit, and look at force control from a distance. This reveals a lot of similarities among different control approaches, and allows us to put force control into a broader (e.g., differential-geometric) context. In order to achieve a high information density this text works with short, explicit statements which are briefly commented, but not proven. Some of these statements are well known and sometimes even trivial, some other reflect the personal opinion and experience of the authors; they may not be generally accepted, or at least require further investigation. Nevertheless we believe this collection of statements represents a useful background for future research in force control.

This paper is organized as follows: Section 2 presents the basics of force control at an introductory level, by focusing at one or two degrees of freedom. Section 3 describes in a general differential-geometric context the problems associated with the extension to the multi-dimensional case. Section 4 discusses robustness and adaptive control. Finally, Section 5 points at future research directions.

## 2 Basics of force control

### 2.1 Basic approaches

The two most common basic approaches to force control are Hybrid force/position control (hereafter called Hybrid control), and Impedance control. Both approaches can be implemented in many different ways, as discussed later in this section. Hybrid control [16, 12] is based on the decomposition of the workspace into purely motion controlled directions and purely force controlled directions. Many tasks, such as inserting a peg into a hole, are naturally described in the ideal case by such task decomposition. Impedance control [11], on the other hand, does not regulate motion or force directly, but instead regulates the ratio of force to motion, which is the mechanical impedance.

Both Hybrid control and Impedance control are highly idealized control architectures. To start with, the decomposition into purely motion controlled and purely force controlled directions is based on the assumption of ideal constraints, i.e. rigid and frictionless contacts with perfectly known geometry. In practice however the environment is characterized by its impedance, which could be inertial (as in pushing), resistive (as in sliding, polishing, drilling, etc.) or capacitive (spring-like, e.g., compliant wall). In general the environment dynamics are less known than the robot dynamics. In addition there could be errors in the modeled contact geometry (or contact kinematics)[1], e.g. the precise location of a constraint, or a bad orientation of a tangent plane. Both environment dynamics and geometric errors result in motion in the force controlled directions, and contact forces in the position controlled directions.[2] Hence, the impedance behavior of the robot in response to these imperfections, which is usually neglected in Hybrid control designs, is of paramount importance. Impedance control provides only a partial answer, since, in order to obtain an acceptable task execution, the robot impedance should be tuned to the environment dynamics and contact geometry. In addition, both Hybrid control and Impedance control have to cope with other imperfections, such as unknown robot dynamics (e.g. joint friction, joint and link flexibility, backlash, inaccurately known inertia parameters, etc.), measurement noise, and other external disturbances.

In order to overcome some of the fundamental limitations of the basic approaches, the following improvements have been proposed. The combination of force and motion control in a single direction has been introduced in the Hybrid control approach, first in [8, 9], where it is termed feedforward motion in a force controlled direction, and more recently in [5, 18], where it is termed parallel force/position control (hereafter called Parallel control). In each case force control dominates over motion control, i.e., in case of conflict the force setpoint is regulated at the expense of a position error. On the other hand, Hybrid control and Impedance control can be combined into Hybrid impedance control [1], which allows us to simultaneously regulate impedance and either force or motion.

### 2.2 Examples

In the first example, Fig. 1 (left), one needs to control the position of a tool (drill) along a straight line in order to drill a hole. This is an example of a (highly) resistive environment. The speed of the motion depends on the environment (hardness of the material), the properties of the tool (maximum allowable force), as well as the robot dynamics (actuator limits, friction, etc.). Hence it is natural to regulate both force and motion in the same direction.

Several strategies might be considered:

[1] As stated in the introduction dealing with geometric uncertainty is an important motivation for the use of force control!

[2] In some cases there is even an explicit need to combine force and motion in a single direction, e.g. when applying a contact force on an object which lies on a moving conveyor belt.

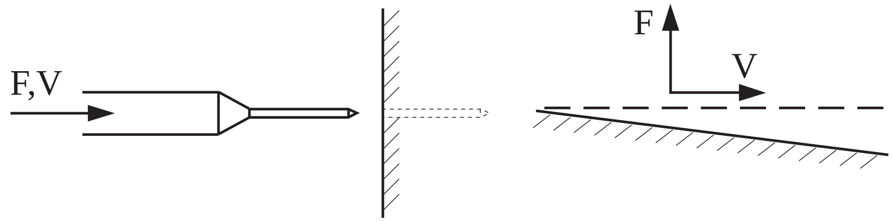


Figure 1: Left: One-dimensional drilling. Right: Following a planar contour.

1. **Pure force control:** A constant force is commanded. The tool moves as material is removed so that position control is not required. The desired force level is determined by the maximum allowable force (so as not to break the drill) and by the maximum allowable speed (so as not to damage the material being drilled). Successful task execution then requires knowledge of the environment dynamics.

2. **Pure position control:** A desired velocity trajectory is commanded. This strategy would work in a highly compliant environment where excessive forces are unlikely to build up and damage the tool. In a stiff or highly resistive environment, the properties of the tool and environment must be known with a high degree of precision. Even then, a pure position control strategy would be unlikely to work well since even small position errors result in excessively large forces.

3. **Pure impedance control:** This approach is similar to the pure position control strategy, except that the impedance of the robot is regulated to avoid excessive force buildup. However, in this approach there is no guarantee of performance and successful task execution would require that the dynamics of the robot and environment be known with a high accuracy in order to determine the commanded reference velocity and the desired closed loop impedance parameters.

4. **Force control with feedforward motion, or parallel force/position control:** In this approach both a motion controller and a force controller would be implemented (by superposition). The force controller would be given precedence over the motion controller so that an error in velocity would be tolerated in order to regulate the force level. Again, this approach would require accurate knowledge of the environment dynamics in order to determine the reference velocity and the desired force level. In a more advanced approach the required reference velocity is estimated and adapted on-line [9].

5. **Hybrid impedance control:** In this approach the nature of the environment would dictate that a force controller be applied as in 1. This guarantees force tracking while simultaneously regulating the manipulator impedance. Impedance regulation, in addition to force control, is important if there are external disturbances (a knot in wood, for example) which could cause the force to become excessive.

In the second example, Fig. 1 (right), the purpose is to follow a planar surface with a constant contact force and a constant tangential velocity. In the Hybrid control approach it is natural to apply pure force control in the normal direction and pure position control in the tangential direction. However, if the surface is misaligned, the task execution results in motion in the force controlled direction, and contact forces (other than friction) in the position controlled direction. In terms of impedance, the environment is resistive (in case of surface friction) in tangential direction, and capacitive in normal direction. Hence it is natural in the Hybrid impedance control to regulate the robot impedance to be noncapacitive in the normal direction, and capacitive in the tangential directions, in combination with force control in normal direction and position control in tangential direction [1]. Hence, a successful task execution would require accurate knowledge of both the environment dynamics and the contact geometry.

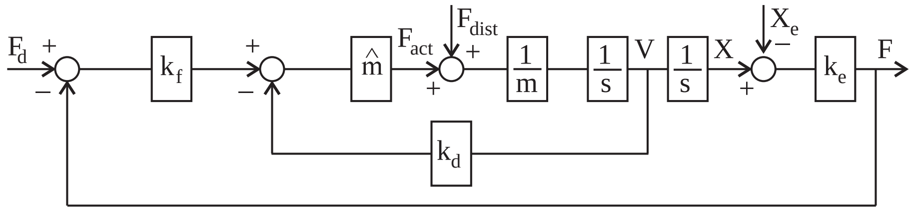


Figure 2: Direct force control.

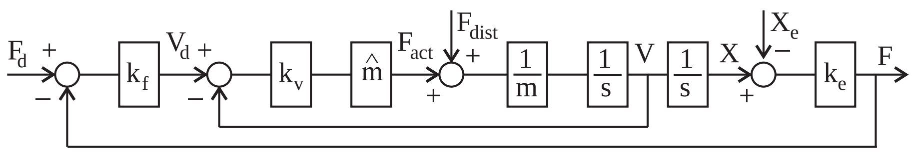


Figure 3: Force control with inner position/velocity control loop.

## 2.3 Basic implementations

There are numerous implementations of both Hybrid control and Impedance control. We only present a brief typology here. For more detailed reviews the reader is referred to [22, 15, 10].

In Hybrid control we focus on the implementation of pure force control. As a first option, measured force errors are directly converted to actuator forces or torques to be applied at the robot joints. This is called direct force control hereafter. Fig. 2 depicts this for the 1 d.o.f. case. The robot has mass $m$, and is in contact with a compliant environment with stiffness $k_e$. $F_d$ is the desired contact force; $F$ is the actual contact force which is measured using a force sensor at the robot wrist; $k_f$ is a proportional force control gain; damping is provided by adding velocity feedback[3], using feedback constant $k_d$; $F_{act}$ is the actuator force; $F_{dist}$ is an external disturbance force; $x$ and $v$ represent the position and the velocity of the robot; $x_e$ represents the position of the environment. Notice that an estimate of the robot mass, $\hat{m}$, is included in the controller in order to account for the robot dynamics. In the multi d.o.f. case this is replaced by a full dynamic model of the robot. As a second option, measured force errors are converted to desired motion, either desired position, or desired velocity, which is executed by a position or velocity control loop. This implementation is called inner position (or velocity)/outer force control. Fig. 3 depicts this for the case of an inner velocity loop. The velocity controller includes a feedback gain, $k_v$, and again a dynamic model of the robot. In many practical implementations however, the velocity controller merely consists of a PI feedback controller, without dynamic model. Feedforward motion can be introduced by adding an extra desired velocity (not shown in figure) to the velocity resulting from

[3]Instead of taking the derivative of measured force signals, which are usually too noisy.

the force feedback control. Comparison of Figs. 2 and 3 reveals that both implementations are very similar. However, the advantage of the inner/outer implementation is that the bandwidth of the inner motion control loop can be made faster than the bandwidth of the outer force control loop.[4] Hence, if the inner and outer loops are tuned consecutively, force disturbances are rejected more efficiently in the inner/outer implementation.[5] Since errors in the dynamic model can be modeled as force disturbances, this explains why the inner/outer implementation is more robust with respect to errors in the robot dynamic model (or even absence of such model).

As for Impedance control, the relationship between motion and force can be imposed in two ways, either as an *impedance* or as an *admittance*. In *impedance* control the robot reacts to deviations from its planned position and velocity trajectory by generating forces. Special cases are a stiffness or damping controller. In essence they consist of a PD position controller, with position and velocity feedback gains adjusted in order to obtain the desired compliance.[6] No force sensor is needed. In *admittance* control, the measured contact force is used to modify the robot trajectory. This trajectory can be imposed as a desired acceleration or a desired velocity, which is executed by a motion controller which may involve a dynamic model of the robot.

## 2.4 Properties and performance of force control

Properties of force control have been analysed in a systematic way in [7] for the Hybrid control approach, and in [1] for the Impedance control approach. The statements presented below are inspired by a detailed study and comparison of both papers, and by our long experimental experience. Due to space limitations detailed discussions are omitted.

**Statement 1** *An equivalence exists between pure force control, as applied in Hybrid control, and Impedance control. Both types of controllers can be converted to each other.*

**Statement 2** *All force control implementations, when optimized, are expected to have similar bandwidths.*

This is because the bandwidth is mainly limited due to system imperfections such as backlash, flexibility, actuator saturation, nonlinear friction, etc., which are independent of the control law. As a result:

**Statement 3** *The apparent advantage of impedance control over pure force is its freedom to regulate impedance. However, this freedom can only be exercised within a limited bandwidth.*

In order to evaluate the robustness of a force controller, one should study: (i) its capability to reject force disturbances, e.g. due to imperfect cancellation of the robot dynamics (cf. section 2.3); (ii) its capability to reject motion disturbances, e.g. due to motion or misalignment of the environment (cf. section 2.1); (iii) its behaviour out of contact and at impact (this is important for the transition phase, or approach phase, between motion in free space and motion in contact).

[4] Force control involves noncollocation between actuator and sensor, while this is not the case for motion control. In case of noncollocation the control bandwidth should be 5 to 10 times lower than the first mechanical resonance frequency of the robot in order to preserve stability; otherwise bandwidths up to the first mechanical resonance frequency are possible, see e.g. [17] for a detailed analysis.

[5] Of course, the same effect can be achieved by choosing highly overdamped closed-loop dynamics in the direct force control case, i.e., by taking a large $k_d$. However, this requires a high sampling rate for the direct force controller. (Note that velocity controllers are usually implemented as analog controllers.)

[6] In the multi d.o.f. case the position and velocity feedback gain matrices are position dependent in order to achieve constant stiffness and damping matrices in the operational space.

**Statement 4** *The capability to reject force disturbances is proportional to the contact compliance.*

**Statement 5** *The capability to reject motion disturbances is proportional to the contact compliance.*

**Statement 6** *The force overshoot at impact is proportional to the contact stiffness.*

A larger approach speed can be allowed if the environment is more compliant. Then, combining statements 5 and 6:

**Statement 7** *For a given uncertainty in the task geometry a larger task execution speed can be allowed if the environment is more compliant.*

**Statement 8** *The capability to reject force disturbances is larger in the inner/outer implementations.*

This is explained in section 2.3.

When controlling motion in free space, the use of a dynamic model of the robot is especially useful when moving at high speeds. At very low speeds, traditional joint PID controllers perform better, because they can better deal with nonlinear friction. Now, the speed of motion in contact is often limited due to the nature of the task. Hence:

**Statement 9** *In case of a compliant environment, the performance of inner/outer control is better than or equal to direct force control.*

However, due to the small signal to noise ratios and resolution problems of position and velocity sensors at very low speeds:

**Statement 10** *The capability to establish stable contact with a hard environment is better for direct force control than for inner/outer control. (A low-pass filter should be used in the loop.)*

# 3 Multi degree of freedom force control

All concepts discussed in the previous section generalize to the multi degree of freedom case. However, this generalization is not always straightforward. This section describes the fundamental physical differences between the one-dimensional and multi-dimensional cases, which *every* force control algorithm should take into account. As before, most facts are stated without proofs.

## 3.1 Geometric properties

(The necessary background for this section can be found in [14] and references therein.) The first major distinctions are between *joint space* and *Cartesian space* (or "operational space"):

**Statement 11** *Joint space and Cartesian space models are equivalent coordinate representations of the same physical reality. However, the equivalence breaks down at the robot's singularities.*

(This text uses the term "configuration space" if joint space or Cartesian space is meant.)

**Statement 12 (Kinematic coupling)** *Changing position, velocity, force, torque,... in one degree of freedom in joint space induces changes in all degrees of freedom in Cartesian space, and vice versa.*

The majority of publications use linear algebra (vectors and matrices) to model a constrained robot, as well as to describe controllers and prove their properties. This often results in neglecting that:

**Statement 13** *The geometry of operational space is not that of a vector space.*

The fundamental reason is that rotations do not commute, either with other rotations or with translations. Also, there is not a set of globally valid coordinates to represent orientation of a rigid body whose time derivative gives the body's instantaneous angular velocity.

**Statement 14** *Differences and magnitudes of rigid body positions, velocities and forces are not uniquely defined; neither are the "shortest paths" between two configurations. Hence, position, velocity and force errors are not uniquely determined by subtracting the coordinate vectors of desired and measured position, velocity and force.*

Statement 13 is well-known, in the sense that the literature (often implicitly) uses two different Jacobian matrices for a general robot: the first is the matrix of partial derivatives (with respect to the joint angles) of the forward position kinematics of the robot; in the second, every column represents the instantaneous velocity of the end-effector due to a unit velocity at the corresponding joint and zero velocities at the other joints. Both Jacobians differ. But force control papers almost always choose one of both, without explicitly mentioning which one, and using the same notation "$J$."

Statement 14 is much less known. It implies that the basic concepts of velocity and/or force errors are not as trivial as one might think at first sight: if the desired and actual position of the robot differ, velocity and force errors involve the comparison of quantities at different configurations of the system. Since the system model is not a vector space, this comparison requires a definition of how to "transport" quantities defined at different configurations to the same configuration in order to be compared. This is called *identification* of the force and velocity spaces at different configurations. A practical consequence of Statement 14 is that these errors are different if different coordinate representations are chosen. However, this usually has no significant influence in practice, since a good controller succeeds in making these errors small, and hence also the mentioned differences among different coordinate representations.

## 3.2 Constrained robot motion

The difference between controlling a robot in free space and a robot in contact with the environment is due to the *constraints* that the environment imposes on the robot. Hence, the large body of theories and results in constrained systems in principle applies to force-controlled robots. Roughly speaking, the difference among the major force control approaches is their (implicit, default) *constraint model*:

**Statement 15** *Hybrid/Parallel control works with geometric constraints.*
*Impedance control works with dynamic constraints.*

Geometric ("holonomic") constraints are constraints on the *configuration* of the robot. In principle, they allow to *eliminate* a number of degrees of freedom from the system, and hence to work with a lower-dimensional controller. ("In principle" is usually not exactly the same as "in practice"...) Geometric constraints are the conceptual model of *infinitely stiff* constraints.

Dynamic constraints are relationships among the configuration variables, their time derivatives and the constraint forces. Dynamic constraints represent *compliant/damped/inertial* interactions. They do not allow to work in a lower-dimensional configuration space. An exact dynamic *model* of the robot/environment interaction is difficult to obtain in practice, especially if the contact between robot and environment changes continuously.

Most theoretical papers on modeling (and control) of constrained robots use a Lagrangian approach: the constrained system's dynamics are described by a Lagrangian function (combining kinetic and potential energy) with external inputs (joint torques, contact forces, friction, ...). The contact forces can theoretically be found via *d'Alembert's principle*, using Lagrangian multipliers. In this context it's good to know that

**Statement 16** *Lagrange multipliers are well-defined for all systems with constraints that are linear in the velocities; constraints that are non-linear in the velocities give problems [4];*

and

**Statement 17** *(Geometric) contact constraints are linear in the velocities.*

The above-mentioned Lagrange-d'Alembert models have practical problems when the geometry and/or dynamics of the interaction robot-environment are not accurately known.

## 3.3 Multi-dimensional force control concepts

The major implication of Statement 14 for robot force control is that there is no *natural* way to identify the spaces of positions (and orientations), velocities, and forces. It seems mere common sense that quantities of completely different nature cannot simply be added, but nevertheless:

**Statement 18** *Every force control law adds position, velocity and/or force errors together in some way or another, and uses the result to generate set-points for the joint actuators.*

The way errors of different physical nature are combined forms the basic distinction among the three major force control approaches:

1. **Hybrid control.** This approach [13, 16] idealizes any interaction with the environment as *geometric* constraints. Hence, a number of motion degrees of freedom ("velocity-controlled directions") are eliminated, and replaced by "force-controlled directions." This means that a hybrid force controller *selects* $n$ position or velocity components and $6 - n$ force components, subtracts the measured values from the desired values in the lower-dimensional motion and force subspaces, multiplies with a weighting factor ("dynamic control gains") and finally adds the results from the two subspaces. Hence, hybrid control makes a conceptual difference between (i) taking into account the geometry of the constraint, and (ii) determining the dynamics of the controls in the motion and force subspaces.

2. **Impedance/Admittance control.** This approach does not distinguish between constraint geometry and control dynamics: it *weighs* the (complete) contributions from contact force errors or positions and velocities errors, respectively, with *user-defined* (hence arbitrary) weighting matrices. These (have to) have the physical dimensions of impedance or admittance: stiffness, damping, inertia, or their inverses.

3. **Parallel control.** This approach combines some advantages of both other methods: it keeps the geometric constraint approach as model paradigm to think about environment interaction (and to specify the desired behavior of the constrained system), but it weighs the complete contributions from position, velocity and/or force errors in a user-defined (hence arbitrary) way, giving priority to force errors. The motivation behind this approach is to increase the robustness; Section 4 gives more details.

In summary, all three methods do exactly the same thing (as they should do). They only differ in (i) the motion constraint paradigm, (ii) the place in the control loop where the gains are applied, and (iii) which (partial) control gains are *by default* set to one or zero. "Partial control gains" refers to the fact that control errors are multiplied by control gains in different stages, e.g., at the sensing stage, the stage of combining errors from different sources, or the transformation from joint position/velocity/force set-points into joint torques/currents/voltages.

*Invariance* under coordinate changes is a desirable property of any controller. It means that the dynamic behavior of the controlled system (i.e., a robot in contact with its environment) is not changed if one changes (i) the reference frame(s) in which the control law is expressed, and (ii) the physical units (e.g., changing centimeters in inches changes the moment component of a generalized force differently than the linear force component). Making a force control law invariant is not very difficult:

**Statement 19** *The weighting matrices used in all three force control approaches represent the geometric concept of a* metric *on the configuration space. A metric allows to measure distances, to transport vectors over configuration spaces that are not vector spaces, and to determine shortest paths in configuration space. A metric is the standard geometric way to identify different spaces, i.c., motions, velocities, forces. The coordinate expressions of a metric transform acoording to well-known formulas. Applying these transformation formulas is sufficient to make a force control law invariant.*

## 3.4 Task specification and control design

As in any control application, a force controller has many complementary faces. The following paragraphs describe only those aspects which are particular to force control:

1. **Model paradigm.** The major paradigms (Hybrid, Impedance, Parallel) all make several (implicit) assumptions, and hence it is not advisable to transport a force control law blindly from one robot system to another. Force controllers are more sensitive than motion controllers to the system they work with, because the interaction with a changing environment is much more difficult to model and identify correctly than the dynamic and kinematic model of the robot itself, especially in the multiple degrees of freedom case.

2. **Choice of coordinates.** This is not much of a problem for free-space motion, but it does become an important topic if the robot has to control several contacts in parallel on the same manipulated object. For multi degrees of freedom systems, it is not straightforward to describe the contact kinematics and/or dynamics at each separate contact on the one hand, and the resulting kinematics and dynamics of the robot's end-point on the other hand. Again, this problem increases when the contacts are time-varying and the environment is (partially) unknown. See [3] for kinematic models of multiple contacts in parallel.

3. **Task specification.** In addition to the physical constraints imposed by the interaction with the environment, the user must specify his own extra constraints on the robot's behavior. In the Hybrid/Parallel paradigms, the task specifiation is "geometric": the user must define the *natural constraints* (which degrees of freedom are "force-controlled" and which are "velocity controlled") and the *artificial constraints* (the control set-points in all degrees of freedom). The Impedance/Admittance paradigm requires a "dynamic" specification, i.e., a set of impedances/admittances. This is a more indirect specification method, since the real behavior of the robot depends on how these specified impedances *interact* with the environment. In practice, there is little difference between the task specification in both paradigms: where the user expects motion

constraints, he specifies a more compliant behavior; where no constraints are expected, the robot can react stiffer.

4. **Feedforward calculation.** The ideal case of perfect knowledge is the only way to make all errors zero: the models with which the force controller works provide perfect knowledge of the future, and hence perfect feedforward signals can be calculated. Of course, a general contact situation is far from completely predictable, not only quantitatively, but, which is worse, also qualitatively: the contact configuration can change abruptly, or be of a different type than expected. This case is again not exceptional, but by definition rather standard for force-controlled systems with multiple degrees of freedom.

5. **On-line adaptation.** Coping with the above-mentioned quantitative and qualitative changes is a major and actual challenge for force control research. Section 4 discusses this topic in some more detail.

6. **Feedback calculation.** Every force controller wants to make (a combination of) motion, velocity and/or force errors "as small as possible." The different control paradigms differ in what combinations they emphasize. Anyway, the goal of feedback control is to dissipate the "energy" in the error function. Force control is more sensitive than free-space motion control since, due to the contacts, this energy can change drastically under small motions of the robot.

The design of a force controller involves the choice of the arbitrary weights among all input variables, and the arbitrary gains to the output variables, in such a way that the following (conflicting) control design goals are met: stability, bandwidth, accuracy, robustness. The performance of a controller is difficult to prove, and as should be clear from the previous sections, any such proof depends heavily on the model paradigm.

# 4 Robust and adaptive force control

Robustness of a controller is its capability to keep controlling the system (albeit with degraded performance), even when confronted with quantitative and qualitative model errors.

**Statement 20 (Definition of robustness)** *Every force controller works with a hierarchy of models: every higher layer imposes additional structure on the configuration space, which allows us to tune the controller and improve its performance. A robust controller is tuned according to a system description at a higher level, but ensures stability of the controlled system if the actual state of the system corresponds to a lower level.*

Robustness is of primary importance to force controllers. Model errors can be geometric or dynamic, as described in the following subsections.

## 4.1 Geometric errors

As explained in Section 2.1 geometric errors in the contact model result in motion in the force controlled directions, and contact forces in the position controlled directions. Statements 4-8 in Section 2.4 already dealt with robustness issues in this respect.

The Impedance/Admittance paradigm starts with this robustness issue as primary motivation; Hybrid controllers should be made robust explicitly. If this is the case Hybrid controllers perform better than Impedance controllers. For example:

1. **Making contact with an unknown surface.** Impedance control is designed to be robust against this uncertainty, i.e. the impact force will remain limited. A Hybrid controller could work with two different constraint models, one for free space motion and one for impact transition. Alternatively, one could use only the model describing the robot in contact, and make sure the controller is robust against the fact that initially the expected contact force does not yet exist. In this case the advantage of the Hybrid controller over the Impedance controller is that, after impact, the contact force can be regulated accurately.

2. **Moving along a surface with unknown orientation.** Again, Impedance control is designed to be robust against this uncertainty in the contact model; Hybrid control uses a more explicit contact model (higher in the above-mentioned hierarchy) to describe the geometry of the constraint, but the controller should be able to cope with forces in "velocity-controlled directions" and motions in the "force-controlled directions." If so, contact force regulation will be more accurate in the Hybrid control case.

Hence, Hybrid control and Impedance control are complementary, and:

**Statement 21** *The purpose of combining Hybrid Control and Impedance Control, such as in Hybrid impedance control or Parallel control, is to improve robustness.*

Another way to improve robustness is to adapt on-line the geometric models that determine the paradigm in which the controller works. Compared to the "pure" force control research, on-line adaptation has received little attention in the literature, despite its importance.

The goal is to make a local model of the contact geometry, i.e., roughly speaking, to estimate (i) the tangent planes at each of the individual contacts, and (ii) the type of each contact (vertex-face, edge-edge, etc.). Most papers limit their presentation to the simplest cases of single, vertex-face contacts; the on-line adaptation then simplifies to nothing more than the estimation of the axis of the measured contact force. The most general case (multiple time-varying contact configurations) is treated in [3]. The theory covers all possible cases (with contacts that fall within the "geometric constraints" class of the Hybrid paradigm!). In practice the estimation or identification of uncertainties in the geometric contact models often requires "active sensing": the motion of the manipulated object resulting from the nominal task specification does not persistently excite all uncertainties and hence extra identification subtasks have to be superimposed on the nominal task. Adaptive control based on an explicit contact model has a potential danger in the sense that interpreting the measurements in the wrong model type leads to undesired behavior; it only increases the robustness *if* the controller is able to (i) recognize (robustly!) transitions between different contact types, and (ii) reason about the probability of different contact hypotheses. Especially this last type of "intelligence" is currently beyond the state of the art, as well as completely automatic active sensing procedures.

## 4.2 Dynamics errors

Most force control approaches assume that the robot dynamics are perfectly known and can be conquered exactly by servo control. In practice however, uncertainties exist. This motivates the use of either robust control or model based control to improve force control accuracy.

Robust control [6] involves a simple control law, which treats the robot dynamics as a disturbance. However, right now robust control can only ensure stability in the sense of uniformly ultimate boundedness, not asymptotic stability.

On the other hand, model-based control is used to achieve asymptotic stability. Briefly speaking, model-based control can be classified into two categories: linearization via nonlinear feedback [20, 21] and passivity-based control [2, 19, 23]. Linearization approaches usually have two calculation steps. In the first step, a nonlinear mapping is designed so that an equivalent linear system is formed by connecting this mapping to the robot dynamics. In the second step, linear control theory is applied to the overall system. Most linearization approaches assume that the robot dynamics are perfectly known so that nonlinear feedback can be applied to cancel the robot dynamics. Nonlinear feedback linearization approaches can be used to carry out a robustness analysis against parameter uncertainty, as in [20], but they cannot deal with parameter adaptation.

Parameter adaptation can be addressed by passivity-based approaches. These are developed using the inherent passivity between robot joint velocities and joint torques [2]. Most model-based control approaches are using a Lagrangian robot model, which is computationally inefficient. This has motivated the *virtual decomposition* approach [23], an adaptive Hybrid approach based on passivity. In this approach the original system is virtually decomposed into subsystems (rigid links and joints) so that the control problem of the complete system is converted into the control problem of each subsystem independently, plus the issue of dealing with the dynamic interactions among the subsystems. In the control design, only the dynamics of the subsystems instead of the dynamics of the complete system are required. Each subsystem can be treated independently in view of control design, parameter adaptation and stability analysis. The approach can accomplish a variety of control objectives (position control, internal force control, constraints, and optimizations) for generalized high-dimensional robotic systems. Also, it can include actuator dynamics, joint flexibility, and has potential to be extended to environment dynamics. Each dynamic parameter can be adjusted within its lower and upper bounds independently. Asymptotic stability of the complete system is guaranteed in the sense of Lyapunov.

# 5 Future research

Most of the “low-level” (i.e., set-point) force control performance goals are met in a satisfactory way: many people have succeeded in making stable and accurate force controllers, with acceptable bandwidth. However, force control remains a challenging research area.

A unified theoretical framework is still lacking, describing the diffferent control paradigms as special limit cases of a general theory. This area is slowly but steadily progressing, by looking at force control as a specific example of a nonlinear mechanical system to which differential-geometric concepts and tools can be applied. Singular perturbation is another nonlinear control concept that might be useful to bridge the gap between geometric and dynamic constraints.

Robustness means different things to different people. Hence, refinement of the robustness concept (similar to what happened with the stability concept) is another worthwhile theoretical challenge.

From a more practical point of view, future research should produce systems with improved intermediate and high-level performance and user-friendliness:

1. **Intermediate-level performance.** This is the control level at which system models are given, which however have to be adapted on line in order to compensate for quantitative errors. Further progress is needed on how to identify the errors both in the geometric and dynamic robot and environment models (and how to compensate for them), and especially on how to integrater geometric and dynamic adaptation.

2. **High-level performance.** This level is (too) slowly getting more attention. It should make a force-controlled system robust against unmodeled events, using “intelligent” force/motion signal processing and reasoning tools to decide (semi)autonomously and robustly when to perform control model switches, when to re-plan (parts of) the user-specified task, when to add active sensing, etc. The required intelligence could be model-based or not (e.g., neural networks, etc.).

3. **User-friendliness.** Current task specification tools are not really worth that name since they are rather control-oriented and not application-oriented. Force control systems should be able to use domain-specific knowledge bases, allowing the user to concentrate on the semantics of his tasks and not on *how* they are to be executed by the control system: the model and sensor information needed to execute the task is extracted automatically from knowledge and data bases, and vice versa. How to optimize the human interaction with an intelligent high-level force controller is another open question.

All these developments have strong parallels in other robotic systems under, for example, ultrasonic and/or visual guidance. Whether force-controlled systems (or sensor-based systems in general) will ever be used outside of academic or strictly controlled industrial environments will be determined in the first place by the progress achieved in these higher-level control challenges, more than by simply continuing the last two decades' research on low-level control aspects.

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