Hybrid Force Control for Parallel Manipulators

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***Abstract*¾ Given the advantages of the lightweight structure of parallel robots a control strategy based on switching control is proposed which improves the characteristics of the transition between free-motion mode and contact-motion mode during force control.**

***Index Terms*¾ Switched systems, exact linearisation, parallel manipulators, force control, Lyapunov functions.**

I. INTRODUCTION

When considering the implementation of force related commands two types of control strategies can take place which are known as indirect force control and direct force control [1]. Within the indirect force control the force measurements do not play the major role in the control algorithm as opposite to the direct force control and the force commands are achieved by bringing in the environment characteristics as stiffness (compliance control) as well as the actual mass and damping at the contact point (impedance control) [2]–[4]. The problem of most indirect force control strategies is that forces cannot be regulated unless the exact environment model is known and it is integrated into the manipulator's motion plan. On the contrary, direct force control schemes, sometimes seen as synonymous of position/force hybrid control have a design that operates directly on the error between the desired and measured force values [5]. Implicit is that little knowledge of the environment is needed to define the control laws which in some cases can lead to contact instability causing peak impulse force and bouncing among other phenomena. Although a way to prevent this to happen is to include some compliance into the manipulator this may not be the best solution for some applications. So a reliable direct force control design will have to provide an algorithm that solves the manipulator/environment interaction when regarding at least three phases, i.e., free motion, contact transition, and force tracking phases [6]–[9]. Such approach is particularly advantageous to the implementation of force control algorithms that can minimise the influence of the phenomena occurring during contact transition, that is, when the end effector reaches the surface of an object where force is supposed to be produced as an interaction between the two. The undesired phenomena happening in this situation are among others bouncing and peak impulsive force. Since they result from the collision of the end effector with an object's surface, knowledge of the impact process as well as its dynamic model have been brought into the design of force control algorithms with the option for different solutions as documented in the references [10]–[14]. Of special interest to this work are the articles [10] and [14] where after feedback linearisation of the manipulator dynamics an event driven switching strategy is used to cope with the above mentioned phenomena.

This work gives a procedure for direct force control, thus limiting the influence of kinematic structural and task uncertainties, that takes into consideration the problematic of the contact transition control. Based on a feedback exact linearised manipulator dynamic model a switching control strategy with four linear controllers is developed in order to guarantee stable contact transition and force regulation. Its advantage when compared with [14] is that it not only uses a impact velocity controller to prevent the injection of large amounts of energy onto the contact surface but also includes a brake controller to dissipate this energy after impact before a force controller is taken into the control loop.

The organisation of this paper is as follows. In Section II a dynamic model for a parallel robot is given and control laws for its exact linearisation and to perform position/force control are presented. There are also given two solutions that avoid the need of the derivative of the measured force in the PID type force control algorithm. The switching control strategy for force control is described and analysed in Section III with its application to the dynamic model of the parallel robot FÜNFGELENK shown in Section IV through simulation results. Finally, conclusions of this work are found in Section V, which ends with the proof of the switching control strategy in Appendix being followed by the References.

II. FORCE CONTROL PROBLEM FORMULATION

Given the structure of a parallel robot and for control purposes, its dynamic equations are preferably defined in cartesian coordinates which for a n degrees of freedom robot results into

$$M(x)\ddot{x} + C(x,\dot{x})\dot{x} + g(x) + F = J^{-T}t \qquad (1)$$

where $M(x), C(x,\dot{x})\dot{x}, g(x)$, and F represent the inertia matrix, the Coriolis and centripetal force, the gravitation force, and the external forces acting on the end effector, respectively. The vectors $\ddot{x}, \dot{x}$ and x express the cartesian accelerations, velocities and displacements, J is the Jacobian matrix and t is the vector of driving torques.

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As usual, to enable a control design within the linear framework the robot's dynamic model is first exact linearised and decoupled by employing feedback linearisation or inverse dynamics in the form of a state feedback law

$$t = J^T \left[M(x)u + C(x,\dot{x})\dot{x} + g(x) + F \right] \tag{2}$$

which renders the dynamic behaviour of the robot similar to that of a double integrator

$$\ddot{x} = u \tag{3}$$

and turns *u* into the new input variable of the exact linearised robot. Of course this procedure assumes that the dynamics of the robot's actuators can be neglected.

To enable for position regulation within the parallel robot system a linear controller is used as defined in [15] where the output variable, u_x, is built upon position and velocity error variables as well as on the feedforward of desired velocity and acceleration

$$\begin{aligned} u_x &= k_Q(x_d - x) \\ u_v &= k_P(u_x + \dot{x}_d - \dot{x}) + k_I \int (u_x + \dot{x}_d - \dot{x})dt \\ u_p &= u_v + \ddot{x}_d \end{aligned} \tag{4}$$

with $\ddot{x}_d, \dot{x}_d$ and x_d the desired cartesian accelerations, velocities and displacements.

Regarding force control the simplest solution is to employ a PID type control law

$$u_f = (\dot{f}_d - \dot{f}) + k_F(f_d - f) + k_I \int (f_d - f)dt \tag{5}$$

which performs well when the end effector is already in contact with the environment and the robot acceleration is taken as equal to zero. Nevertheless, and considering that these conditions are fulfilled, equation (5) is difficult to implement because the measured force is contaminated with noise which is passed to the term $(\dot{f}_d - \dot{f})$ even when filtering is applied. So that reliable solutions have to used instead a substitute term based on the information given by the velocity of the robot's end effector.

A. With estimation of stiffness of the environment

The first approach is to substitute this term with $(\dot{f}_d - \hat{k}_e\dot{x})$ where $\hat{k}_e$ is the estimated value of the stiffness of the environment. This approach works well if the environment has low values of stiffness or when this is not the case the estimated value represents the stiffness of the robot. Expression (5) is then modified to

$$\begin{cases} u_f = k_D(\dot{f}_d - \hat{k}_e\dot{x}) + k_P(f_d - f) + k_I \int (f_d - f)dt \\ \dot{\hat{k}}_{e_f} = -\dot{x}(f_d - f) \end{cases} \tag{6}$$

which results in a closed loop system having a dynamic behaviour equal to

$$\begin{aligned} & k_D(\dot{f}_d - (k_e - \bar{k}_e)\dot{x}) + k_P\dot{e}_f + k_I e_f = 0 \\ & e_f = -\frac{k_P}{k_I}\dot{e}_f - \frac{k_D}{k_I}\ddot{e}_f - \frac{k_D}{k_I}\bar{k}_e\dot{x} \end{aligned} \tag{7}$$

if it is taken that $u = u_f$, $\ddot{x} = 0$, $e_f = \int (f_d - f)dt$ and $\bar{k}_e = k_e - \hat{k}_e$.

B. Using robustness towards the stiffness of the environment

In this case knowledge about the expected values of the stiffness of the environment is used to validate the substitution of the term $(\dot{f}_d - \dot{f})$ with the term $-k_D\dot{x}$. Having that in consideration the value of k_D is chosen so that the force controller provides enough damping for all its operating conditions. Equation (5) in then replaced by

$$\begin{aligned} u_f &= -\frac{k_D}{k_e} k_e\dot{x} + k_P(f_d - f) + k_I \int (f_d - f)dt \\ &= -\frac{k_D}{k_e}\dot{f} + k_P(f_d - f) + k_I \int (f_d - f)dt \end{aligned} \tag{8}$$

that implies a closed loop system with a dynamic response defined through

$$\ddot{e}_f + \frac{k_P}{k_F}\dot{e}_f + \frac{k_I}{k_F}e_f = 0 \tag{9}$$

when $u = u_f$, $\ddot{x} = 0$, $\dot{f}_d = 0$ and $e_f = \int (f_d - f)dt$.

The force control strategy just presented with a single type of controller requires that its parameter values have to be chosen to cope appropriately with the transition phases that occur during a force control task which is by itself a complex exercise and if though satisfactory fulfilled it does not prevent the robot's end effector of being accelerated towards the surface of the object where force is to be reached therefore increasing the impact velocity which can cause bouncing and other undesired phenomena. This situation is worsened if the motors and sensors used in the robot have limited dynamics as is proved with the simulation results shown in Section IV.

III. SWITCHING CONTROL STRATEGY FOR FORCE CONTROL

To avoid the compromises and disadvantages of force control strategies with a single controller a force control algorithm based on an event driven switching control strategy where the switching event is taken as force detection was already presented in [14]. That switching control design employed a velocity controller that allowed for impact velocity regulation and which would bring the end effector onto the surface where force was to be produced, a force controller that would be put into the control loop whenever a given force threshold was reached and a position controller for the case that bouncing had occurred and which was able to make the end effector to contact again the surface but now with zero impact velocity. That control strategy performed well because it was able to regulate the impact velocity but had no mechanism to dissipate the kinetic energy when the end effector makes the first contact with the object's surface other than the proper force controller. This would overload the force controller for high impact velocities or for environments with high stiffness.

The new switching control strategy is able to provide a solution to this problem by employing a fourth controller that assures that the kinetic energy gained before contact has a way to dissipate other than that given when the force controller is in the control loop. This fourth controller, so-called brake controller, is in the loop after contact time long enough to slow down the end effector to a value that is appropriate for the takeover of the control loop by the force controller. The design of this switching control strategy is done taking into consideration a task force configuration as shown in Fig. 1 where it can be seen that initially the end effector is in free space far from the point where the desired force value is to be produced, f_d.

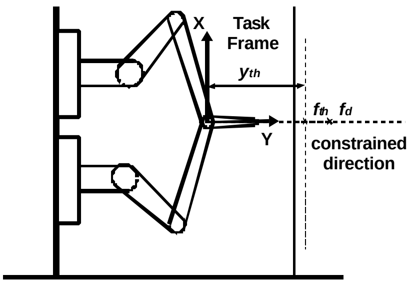


Fig. 1. Typical configuration of a task force.

With reference to Fig. 1 the switching force control algorithm as given by equation (10) will first use a velocity controller to bring the end effector onto the surface with a defined impact velocity, v_d, then and after detection of a threshold force, f_{th}, the brake controller is put into the control loop for a given time, t_I, to slow down the end effector. As soon as this brake time, t_I, has elapsed a force controller is activated so that the desired force command will be achieved. If eventually bounce occurs and the end effector loses contact with the surface a position controller will be put into the control loop so that the end effector will return with zero velocity to the point where the threshold force was first measured, y_{th}. After this the force controller will be placed again in the control loop.

$$\begin{cases} \text{if } \left[(f \geq f_{th}) \ \& \ \text{not already } D\right] \text{ then } B \\ \text{elseif } \left[(f \geq f_{th}) \ \& \ \text{already } B\right] \text{ then } D \\ \text{elseif } \left[(f < f_{th}) \ \& \ \text{not already } D\right] \text{ then } A \\ \text{elseif } \left[(f < f_{th}) \ \& \ \text{already } D\right] \text{ then } C \end{cases} \tag{10a}$$

$$\begin{cases} \text{if } A \text{ then } u_f = k_V(v_d - \dot{y}) \\ \text{if } B \text{ then } u_f = -k_B\dot{y} \\ \text{if } C \text{ then } u_f = -k_D\dot{y} + k_P(y_{th} - y) \\ \text{if } D \text{ then } u_f = (\dot{f}_d - \dot{f}) + k_F(f_d - f) + k_I\int(f_d - f)dt \end{cases} \tag{10b}$$

As seen in equation (10b) the force controller has no acceleration term because it is also assumed that during force control the values of acceleration remain too small to be critical to the stability of the closed loop system although this may not be valid for the instants after impact where the values of the acceleration transients depend on the impact velocity and the characteristics of the environment. Nevertheless, this assumption was taken as appropriate for the stability analysis of the proposed force control algorithm because included in the control loop are elements that tend to smooth out the effects of these transients as for instance the brake controller and the low-pass filters connected to the robot's sensors. The stability analysis of this force control algorithm is given in the Appendix and here are only stated in form of a theorem the required conditions for stability. The outline of the proof is that if each controller activated by the switching law is able to stabilise the system and to bring its states to the conditions imposed by the desired input commands as defined by the same switching law, then the system will be in a finite number of switchings under force control and the force equilibrium point will be reached. In Fig. 2 is a graphic representation of the proposed switching control strategy.

Theorem 1: The parallel robot (1) exact linearised through the application of the inverse dynamic (2), will asymptotically converge to the equilibrium point, $f_d - f = 0$, when the force control algorithm defined by (10) is used, if and only if the parameters of this control algorithm satisfy the following conditions

$$\begin{gathered} k_V > 0;\ k_B > 0;\ k_D > 0 \ \text{ and} \\ k_P > 0; \ \text{and } \frac{k_F}{\sqrt{k_I}} > 0 \end{gathered} \tag{11}$$

The switching control strategy requires the estimation of the period of time, t_I, during which the brake controller remains in the control loop. For that it must be remembered that the usefulness of this strategy comes also as a means to improve control performance despite dynamic and stroke or range limitations of actuators and sensors within the robotic system. Ultimately, this control algorithm will also suffer from such restrictions namely with regard to the amount of improvement brought to the control system over its many operating conditions, that is, robot attitude, impact velocity and stiffness of the environment. A closer analysis permit to assert that the brake time, t_I, is dependent of the actuator's dynamics and indirectly of the gain of the brake controller, k_B, the impact velocity, v_I, and the stiffness of the environment, k_e. Although this function, $t_I = f(k_B, v_I, k_e)$, is difficult to obtain analytically a satisfactory approximation based on empiric data can be easily found when the gain of the brake controller is taken as an already defined fixed parameter. It can be verified that for low values of environment stiffness and of impact velocity the time during which the brake controller has to be in the control loop is equal to zero, so there is no need for this type of action. Above certain values of these two factors, $f(k_e, v_I)_{\min}$, it has a low limit value, $t_{I\min}$, which grows almost in a linear way till an upper limit value is reached, $t_{I\max}$, that reflects the restrictive characteristics of sensors and actuators in the control loop. Further increases on t_I do not bring any benefit to the quality of control. Simulation results that show the influence of the brake time, t_I, on the possible control performance are given in Section IV.

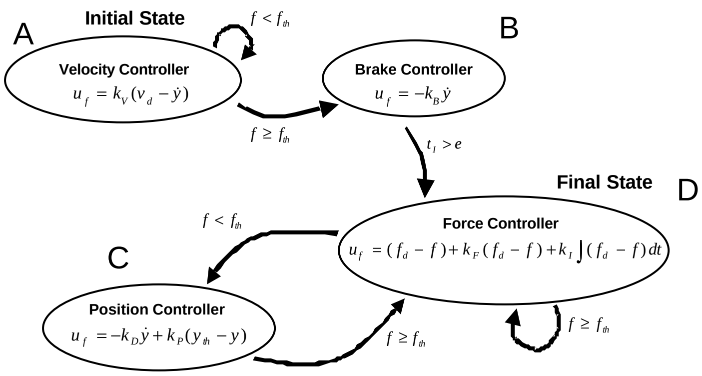


Fig. 2. State diagram of the switching control strategy.

IV. Simulation Results for Parallel Robot Fünfgelenk

The above mentioned control algorithm is to be implemented on the parallel robot FÜNFGELENK[1] which is a 5-joint parallel robot with symmetric structure that has its working space on the vertical plane, see Fig. 3. Its two active joints will be actuated by direct drive motors able to deliver torques of 70*Nm* up to speeds of 2.5*rps*. The direct drive motors carry resolvers to measure shaft angles so that the position of the end effector is calculated through the robot's direct kinematics. Others sensors to be used are force sensors that will be placed near to the end effector. Further characteristics about this parallel robot are listed in Table I.

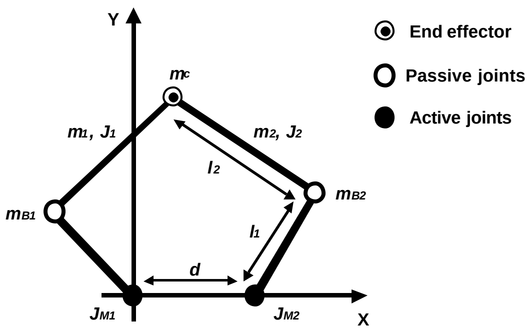


Fig. 3. Structure of the parallel robot FÜNFGELENK.

TABLE I
KINEMATIC AND DYNAMIC PARAMETER VALUES OF THE PARALLEL ROBOT FÜNFGELENK

Parameters	**Values**
m_c	0.7kg
m_1, m_2	0.1kg
m_{B1}, m_{B2}	0.2kg
J_1, J_2	0.015kgm^2
J_{M1}, J_{M2}	0.036kgm^2
l_1	0.3m
l_2	0.5m
d	0.3m

[1] This parallel robot was built during the DFG project SFB 562, Germany.

In order to better evaluate the performances of the force control algorithm prior to implementation a dynamic model of the parallel robot was built in MatLab/Simulink. Also brought into the model are the 1st order dynamics of the motors and sensors with the motors having the slowest dynamics, and torque limitations for the motors which makes the results more reliable for practical purposes. The characteristics of the environment are also regarded in the simulation, although by using a model without dynamics, that is, where the resulting environmental forces are directly proportional to the deformations occurring in the environment.

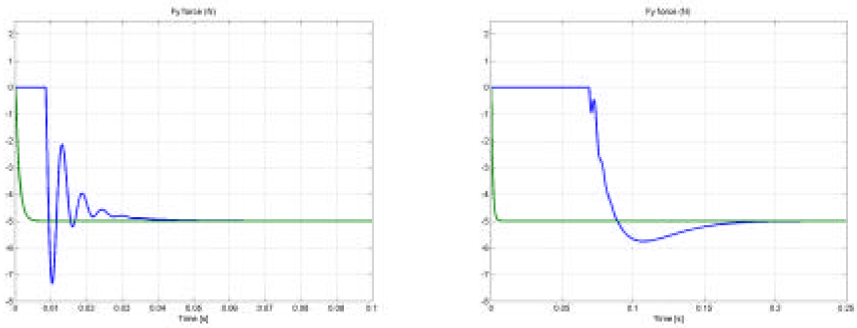
The performed simulation tests considered situations where the end effector was initially not in contact with the object where forces were to be produced and regarded the use of the PID control law (5) and the switching control strategy (10). In Fig. 4 and 5 are shown comparative results for these two control strategies and Fig. 6 gives information about the influence of the brake time, t_I, on the achieved control quality when employing the switching control strategy.

V. Conclusion

The switching control strategy for force control was able to show better control performance when compared with the PID control law, although both strategies are not able to compensate properly when the fast dynamics of the parallel robot is excited due to high values of the impact velocity or stiffness of the environment but this happens mainly because of the slow dynamic characteristics of the robot's actuators. The advantages of the switching control strategy for force control are its ability to regulate the impact velocity and to provide an effective way to dissipate kinetic energy before force control takes place thus avoiding high magnitude and duration transients that would occur in the control loop and would cause stress on the robot's structure.

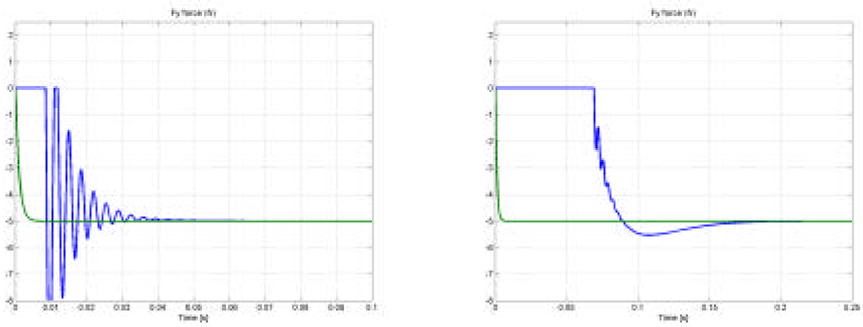
Appendix

The stability proof of the proposed force control algorithm uses the framework already available for the analysis and design of switched system as given in [16], [17] and the references therein. Not going into details, the reader is invited to read the references already mentioned for deeper insight, a



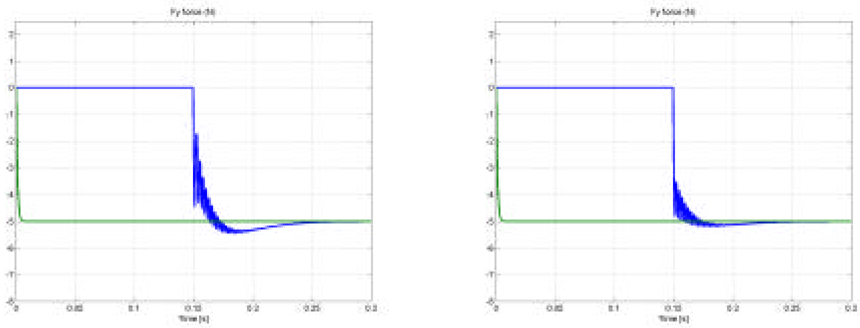
(a) (b)

Fig. 4. Environment stiffness, $k_e = 2000N/m$: (a) PID, $y_{th} = 0.01m$, and (b) switching control strategy, $v_d = 0.5m/s$.



(a) (b)

Fig. 5. Environment stiffness, $k_e = 5000N/m$: (a) PID, $y_{th} = 0.01m$, and (b) switching control strategy, $v_d = 0.5m/s$.



(a) (b)

Fig. 6. Switching control strategy with different brake times: (a) $t_I = 0.4ms$ and (b) $t_I = 1.5ms$.

switched system can be represented by a differential equation of the form

$$\dot{x} = f_{i(s)}(x) \;\text{ with }\; i(s) \in Q \equiv \{1,\ldots,N\} \tag{12}$$

where, $f_{i(s)}$, is a set of sufficiently regular functions from $\Re^n$ to $\Re^n$ that define the system behaviour accordingly to a piecewise constant function of time or events, called switching signal.

One way to prove stability in switched systems is by using multiple Lyapunov functions and to look if they with the switching signal lead to equilibrium points of the system. This will be satisfied at any time if the conditions stated in the following theorem are fulfilled.

Theorem 2: If the switched system (12) has for every system function, $f_{i(s)}$, a Lyapunov function, $V_{i(s)}(x)$, that decreases on each interval where this system function is active then the switched system is asymptotically stable. That is

$$\begin{array}{l} \forall p,q \rightarrow p<q \qquad \exists r>0 \\ V_{i(s(q))}(x_q) - V_{i(s(p))}(x_p) \le -r \quad \Rightarrow \quad x(t) \rightarrow x_{equilibrium} \end{array} \tag{13}$$

Within this framework the stability proof is obtained in two steps. First it is verified that the system under control of each of the controllers defined by (10b) is stable and that its state variables converge to the references, y_{th} or f_d. Second and in the sequel, that accordingly to the switching law (10a) the system variables will always enter the domain of the force controller, that is, $y \rightarrow y_{th}$.

When the parallel robot is controlled by the velocity controller its dynamics is given by, $\ddot{y} = k_V(v_d - \dot{y})$. Changing variables, $e = v_d - \dot{y}$, and choosing Lyapunov function, $V(e) = \frac{1}{2}e^2$, it comes that, $\dot{V}(e) = -k_V e^2$, so the system is stable and converges to, $v_d - \dot{y} = 0$, which implies, $y \to y_{th}$, if parameter conditions (11) of Theorem 1 are met. When the parallel robot is controlled by the brake controller the system dynamics is defined by, $\ddot{y} = -k_B\dot{y}$. Again by changing variables, $e = 0 - \dot{y}$, and taking Lyapunov function, $V(e) = \frac{1}{2}e^2$, it results that, $\dot{V}(e) = -k_B e^2$, and the system is stable and it will bring the end effector to a position y such that, $y > y_{th} \Rightarrow g^{-1}(y) > f_{th}$, in case parameter conditions (11) are again satisfied. Similar is the case when the robot is under control of the position controller. The system dynamics is equal to, $\ddot{y} = -k_D\dot{y} + k_P(y_{th} - y)$, and with variables, $e = y_{th} - y$, and having, $V(e,\dot{e}) = \frac{1}{2}k_P e^2 + \frac{1}{2}\dot{e}^2$, as the system's Lyapunov function, calculations provide the result, $\dot{V}(e,\dot{e}) = -k_D\dot{e}^2$, which shows that the system will be stable and will make, $y_{th} - y = 0$, and as consequence, $y \to y_{th}$, if parameter conditions (11) are verified. Given that in the case of force control, acceleration is assumed equal to zero the system's dynamics is described by equation, $\dot{e}_f + k_F e_f + k_I\int e_f dt = 0$, with $e_f = f_d - f$. Redefining variables, $e = \int e_f\, dt$, the Lyapunov function, $V(e,\dot{e}) = \frac{1}{2}k_I e^2 + \frac{1}{2}\dot{e}^2$, will have a negative definite derivative, $\dot{V}(e,\dot{e}) = -k_F\dot{e}^2$, if parameter conditions (11) hold and doing so, it is valid that, $f \to f_d$.

Now analysing switching law (10a) it is observed that the velocity or position controllers will be active as long as, $f < f_{th}$, with v_d pointing towards y_{th} and $f_{th} = g^{-1}(y_{th})$. For the case that, $f \geq f_{th}$, the brake controller will be brought one time into the control loop and will imply $y > y_{th} \Rightarrow g^{-1}(y) > f_{th}$. Being that, $f = g^{-1}(y)$, belongs to the domain of the force controller, $f \geq f_{th}$, the parallel robot system always reaches the equilibrium point, f_d, as it was intended.

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