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Slack strategy for cable driven haptic interfaces

Justine Saint-Aubert, Stéphane Régnier and Sinan Haliyo

Abstract—Common haptic devices induce interaction with users by transmitting direct forces, corresponding to a coupled environment. Paradoxically, because of their intrinsic mechanical limitations they struggle in cases where this last requires null forces. Cable mechanism are investigated to improve this situation thanks to their low structural inertia. However, current control approaches on these interfaces implies that all cables are always under tension. Consequently, the user is permanently linked with the mechanism and is therefore subject to friction and rotor inertia from actuators. He/She constantly feels these parasites forces even during free exploration. As an alternative, we propose to physically disconnect the user from actuators by selectively slacking some cables when no forces are required. The contact is rendered by ensuring that slack runs out right at this moment. A pilot experiment tests the feasibility of this new approach. Benefits and drawbacks on perception are explored as well as consequences on movement. Beyond the expected cancellation of vibrations and perceived inertia during the free motion, results show a large improvement on velocity performances. They also warn about a *funnel effect* on contact due to shortcomings of the prediction of the point of collision.

I. INTRODUCTION

Nature has extensively used cables for large lightweight structures or force transmission, as in spider webs or tendons. In mechanics, wires are often used to transmit a force from a ground-mounted motor to a moving part, thus the mechanism does not carry the additional load induced by the actuator. Consequently, there is a growing interest for cables in the design of robotic systems [1], [2].

Because of their intrinsic anisotropy, wires are capable of developing only tensile forces. A system with n degrees of freedom requires at least $n+1$ cables and the force on the end-effector is the vector sum of each wire. Tendon-based Stewart platforms, referred as cable robots, are parallel mechanisms where the end-effector is suspended by wires only, each one attached to a motor on the ground [3], [4]. They yield a particularly low mechanical impedance. Indeed, these robots can develop high speed and high forces [5] over large distances while keeping the structural inertia quite low. This property is beneficial to achieve transparent haptic interfaces [6]. Sato proposed first such an innovative device where the end-effector, which can be a handle or a finger cap, is held by wires inside a workspace of tetrahedral shape comprised in a cubic frame [7].

Despite the development of few similar cable haptic devices, the mechanical flexibility of wires themselves is

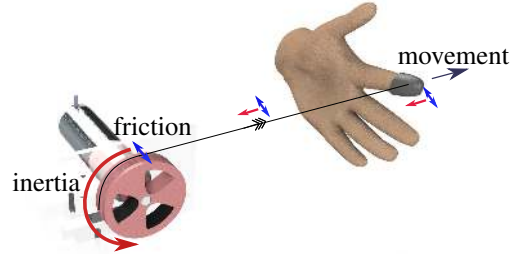


Fig. 1: In impedance control, the user carries the mechanism. Parasitic forces such as friction and inertia are transmitted to his finger via the wire, even in free space.

not yet exploited. The cables are kept taut at all times by supplying each motor a certain amount of current. Therefore, those interfaces are controlled as classical rigid devices. Notably, in bilateral coupling between real or simulated environments and haptic interfaces, two approaches are considered depending on the chosen causality: impedance or admittance [8]. In the former, the device transmits the user motion to the coupled environment and receives in turn a force reference. The wires themselves are used to infer the position, based on motor encoders. In admittance, the device acquires the user-exerted efforts and generates a motion depending on the coupled environment [9]. This requires a force sensor in the handle, as it is difficult to deduce precisely this information directly from motors in a cable interface. It also involves a closed-loop motion control considering the user's input as a perturbation to reject, which can be difficult to implement reliably.

Both approaches have their strengths and weaknesses. Nevertheless, the impedance approach is most widely adopted because of its relative simplicity in control and realization. It also gives a much straightforward behaviour in free space motion, i.e. when simulating null forces. In this case however, because the user drives the entire device, mechanical noise like friction and rotor inertia from each motor are transmitted to the user as depicted in Fig. 1. In a parallel mechanism, these parasitic effects are summed from each thread, increasing with the degrees of freedom [10]. Even if these effects can be compensated in control, this strategy would require an ideal force sensing at the handle and/or predicting the human movement, thus is very difficult to achieve reliably. An alternative strategy consists on physically isolating the user from flaws of the mechanism. This can be achieved by selectively linking or dissociating some actuators, or by for example inserting a passive viscous coupling between actuators [11].

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As a similar simple solution in a cable-driven haptic interface, we propose a strategy to isolate the user for the motors by slacking some cables during free manipulation. This approach aims to cancel most forces during free exploration, without altering the impedance on contact. In a first part, we briefly remind some useful notions on cable interfaces then we introduce the slacking strategy. We finally test the new concept in a pilot experiment.

II. KINEMATICS OF A CABLE INTERFACE

In a cable interface, wires are wrapped around a motor on one extremity and attached to the end-effector on the other. User moves this last, which can also be attached to its fingers.

As wires can only pull, the force which can be generated on it depends on the spatial position of the handle in the workspace and is the vector sum several cables. Therefore each couple of cable is able to return a force vector included in the variable triangle formed by their motors and the end-effector as on Fig. 2a. To exert force in every direction i.e to be fully constraint, the end-effector must be surrounded by motors thus a n degrees of freedom feedback needs at least $n+1$ wires. The fixed workspace is the interior of a volume defined by its corners where the cables are attached as depicted on Fig. 2b and outward forces are more difficult to generate close to workspace boundaries. Motor encoders are used to measure the lengths of cables, themselves used to infer the position of the end-effector. From this location, the contribution of each cable is deduced in order to obtain a force output corresponding to the desired simulated environment. This can be expressed as a Jacobian matrix. In a 3DoF system, the minimum number of wires should be 4, giving an asymmetric matrix between the output force \mathbf{F} and tensions on each wire f_i :

$$\begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = \begin{pmatrix} u_{1x} & u_{2x} & u_{3x} & u_{4x} \\ u_{1y} & u_{2y} & u_{3y} & u_{4y} \\ u_{1z} & u_{2z} & u_{3z} & u_{4z} \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{pmatrix} \quad (1)$$

with $u_w d$ unitary directional vector of the w wire in the direction d .

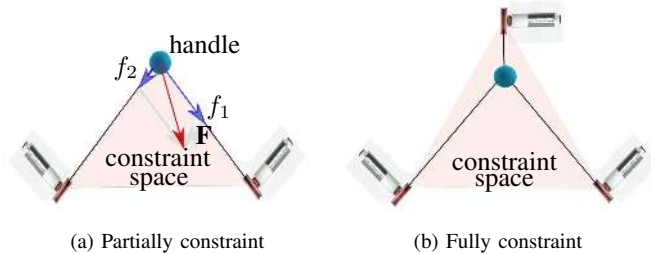


Fig. 2: The constraint space created by two motors is located between their two respective wires (a). Therefore, to be fully constraint in 2D, the mechanism needs at least 3 motors (b).

Inverting (1) can be performed using a pseudo inverse 4×4 matrix. A set of solutions is provided by introducing a vector in the null space, pondered by a free parameter [12]. This parameter is generally used to guarantee that wires are taut at all times [13].

Hence, when no output force is required ($\mathbf{F} = 0$), wires compensate each others and no tension ($f_i \neq 0$) on each wire is not an acceptable solution. The taut condition implies that the user is permanently connected to actuators. Hence, she/he is subject to their mechanical impedance

III. SLACKING STRATEGY

The quality of a haptic interaction is sorely dependent on the capacities of the interface in two situations, and their transition: free exploration and contact. In the former the user has to be clear of any forces. Nevertheless, in case of collision the mechanism must quickly generate a high rigidity. This transition is paramount to the realism of a haptic simulation. However, the apparent rigidity of a real contact is generally above $10^4 N/m$, clearly beyond the capabilities of all DC motor based interfaces. A wire robot is a promising solution in this regard because of the reduced mass vs high forces. Nevertheless, if cables are taut at all times, mechanism behave as rigid solids and propagate parasite efforts without dissipation. Notably, friction and rotor inertia are transmitted via this cable to the user, deteriorating the free space case.

The strategy proposed here is to slack some wires during the free exploration phase. The difficulty is therefore to ensure the transition to contact. Our approach during exploration is to let the right amount of slack on cables as it will run out at contact just in time to simulate an impact. This also should be done while avoiding a hard acceleration on the motors at the last moment. The suggested approach is to try to predict the location of the contact, choosing which cables will contribute to impact and preparing in advance the correct amount of slack. In a 3DoF system, three wires are sufficient to render a force depending on its direction. The last one may detain some slack. A strategy to choose the role of each cable is explained next.

A. Wire selection

Keeping only three necessary wires to exert a 3D force is equivalent to using a 3×3 portion of the Jacobian matrix by removing a slacked wire. Equation (1) becomes :

$$\begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = \begin{pmatrix} u_l x & u_m x & u_n x \\ u_l y & u_m y & u_n y \\ u_l z & u_m z & u_n z \end{pmatrix} \begin{pmatrix} f_l \\ f_m \\ f_n \end{pmatrix} \quad (2)$$

with l, m and n the appropriate combination of three wires. \mathbf{F} can be generated by these three wires if its vector is comprised in a tetrahedron formed by their respective motors and the end-effector Fig. 3. Thus, this combination depends both on the position of the handle and the orientation of the required force vector at the contact point. Knowing if a vector is inward a volume is a common geometrical problem. It can be solved by comparing the scalar products between

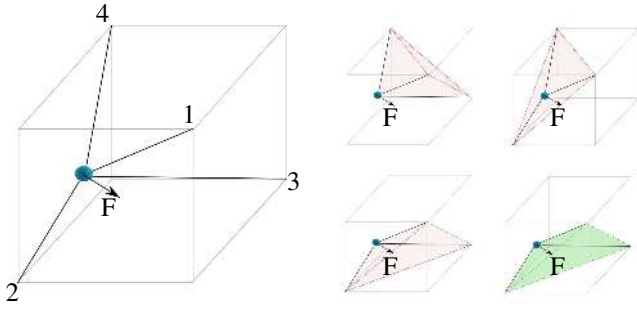


Fig. 3: The set of forces described by three wires is a tetrahedron formed by their three motors and the end-effector. In this example, only the combination 123 can produce \mathbf{F} .

this vector and the normal of each face of the considered volume. In the case of cable mechanisms, each normal is the cross product between the direction of two wires, infer themselves from the actual position \mathbf{P} and motors position.

B. Slack prediction algorithm

The slacking strategy presented above may improve the null-force case. However, in order to properly render contact, a real time control must be established. To insure a realistic impact, an algorithm based on the distance d from handle current position to a predicted contact point, is depicted in Fig. 4. Length L_{si} of slacked wire i is established to cover exactly this distance. In this way, no delay remain when force must be exerted. During the movement, cable which are not carried by the user are kept taut.

The prediction of the contact point is the sensitive point of this strategy. Interesting methods can be synthesized from actual trajectory and current speed vector. Here, as a preliminary and primitive approach to prove the concept, the shortest distance to a rigid object is considered. Concretely, the actual position of the end-effector \mathbf{P} is inferred with a camera sensor. Shortest distance to the rigid object in the simulation is chosen as contact point \mathbf{P}_c and the inverse kinematic gives the corresponding L_{si} at this localisation. With information provided by encoders, lengths are regulated in consequence. This algorithm requires continuous position control to avoid excessive slack generated by friction of cable on wrapper.

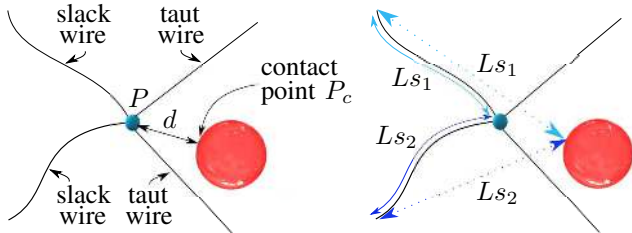


Fig. 4: Slack lengths L_{si} are adjusted in real time depending on the distance d between the end-effector (blue) and the predicted contact point with the simulated object (red).

Note that this algorithm will not work properly in intricate simulations. It will need much more complex methods. Nevertheless, before moving to such complex cases, it would be interesting to prove if the impact is well perceived through the slack running out. In that aim, we implement this new approach in a simple experiment.

IV. EXPERIMENTATION

To evaluate the rendering of an impact through cables running out of slack, we devised a 2D experiment coupled with a virtual scene. Proposed strategy is compared with an impedance based zero-slack control during a free simulation leading to a contact with a wall.

A. Experimental set up

The complete device is presented in Fig. 5. We used four cables with motors placed in plan to constraint two degrees of freedom in translation. To provide visual reference, we add a virtual scene corresponding to the simulated force using *Blender*¹. A realistic interaction is obtained by overlapped in the same space these graphics cues with haptic ones. The system depicted in Fig. 6 provides these co-localized feedbacks, with a monitor placed above a semi-reflective surface [14] and the cable interface below.

The haptic device was designed cautiously to, as much as possible, not handicap the taut method. It combines small size (80cm square) and low power motors (*Maxon DCXL32 70W*) synonym of low rotor inertia. As stated above, positions close to borders of the working space are to avoid because require high power. No reductor were used to avoid backlash and friction. Motors were connected to the handle, a sphere of 5cm in diameter, via light and rigid wires (*Spectra* diameter 1mm). Winders on motors allow for approximately 13cm of slack cable without escaping trouble.

¹<http://www.blender.org>



Fig. 5: Complete device used for the pilot experiment.

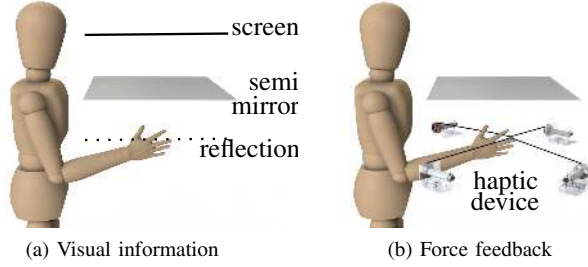


Fig. 6: The user sees across a semi mirror the reflection of the screen, his hand and the virtual scene are visually superimposed (a). The haptic feedback is in the same space, i.e co-localized (b).

B. Control set up

In free case, the taut mode solely means the right amount of current to guarantee compensation of forces and a rigid connection. On the contrary, the slacking mode requires a permanent position control to regulate cable length but also prevent involuntary motion of motors generated by friction between wire and wrapper.

In case of contact, the reaction force \mathbf{F} is deduced from the penetration depth \mathbf{e} (impedance mode). In the experiment, collisions are considered simple and can be directly modelled as a spring-damper model:

$$\mathbf{F} = K_p \mathbf{e} + K_d \frac{d\mathbf{e}}{dt} \quad (3)$$

A stable and rigid contact is obtained with $K_p=1000$ and $K_d=5$ in the taut mode. However, in slack mode, actuators need to change from position to force regulation. This switch is a potential source of instability. An alternative strategy consists on blocking motors at the desired slack length is implemented. A PD controller on each motor with gains (K_{pm}, K_{dm}) equivalent to the contact model of (3) will reproduce forces when wires are taut. For each motor, the control gains are deduced as :

$$f = K_{pm} l + K_{dm} \frac{dl}{dt} \quad (4)$$

with f and l respectively force and error length on a wire. For example for contact point on the vertical symmetry plane of wires $e = l \cos \theta$ and $f = \frac{F}{2 \cos(\theta)}$ with θ the angle between

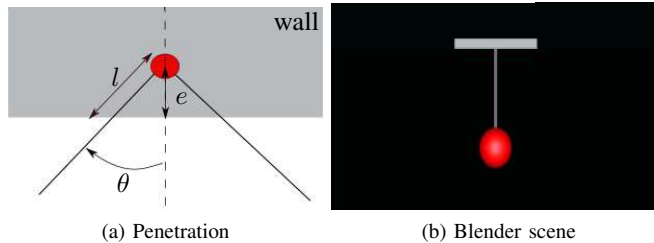


Fig. 7: Penetration length l and depth e in a wall (a). Initial ball position and the wall are visible on a virtual scene (b).

active wires and the generated contact force as in Fig. 7a. Hence, for each wire :

$$K_{pm} = \frac{K_p}{2} - K_d \frac{d\theta}{dt} \tan \theta ; \quad K_{dm} = \frac{K_d}{2} \quad (5)$$

C. Protocol

Users were presented with a scene with an object to handle and a virtual wall. Starting in the free space, they were asked to follow with the object a shown straight line leading to the wall. As the contact point is imposed, this set up allows for a straightforward handling of slack lengths without requiring a prediction algorithm. Some results were based on the subjective assessment of users on both situations, after they complete the whole experiment. To differentiate the two conditions during the simulation, a color code was used on the virtual object, blue (*slack*) or red (*taut*). Users didn't know the strategy beyond this code.

The user held the end-effector with his dominant hand. No indications on the way to hold it was given, except to, as much as possible, not touch wires. Initially a white sphere is projected and the subject is asked to place to handle at this location. After ten seconds, the sphere changes from white to blue or red according to the simulated strategy. At the same moment, a wall appears at variable distance from the starting point with the white guide line as in Fig. 7b. The user is invited to come in slight contact with the virtual wall and then to return to the starting point. No avatar was superimposed with the end-effector during simulation. The distance to wall varies between 4 to 13 cm, following a predefined random pattern.

The experiment consists on 3 sets of 20 trials each, also randomly predefined. Tests were performed in a row. A break of five minutes was given between series. Users were subjected to pink noise emitting headphones to isolate them from eventual acoustic cues coming from motors or cables. Moreover, the interface was concealed in dark to hide cables. A total of eight volunteers (two females) aged from 23 to 30 years old (average 26) have participated. They were all strongly right-handed according to Coren [15]. Everybody (except two) was familiar with robotics systems and only two of them were knowledgeable on haptic devices.

D. Results

For an objective assessment, users performances in term of mean velocities and forces were recorded in both modes.

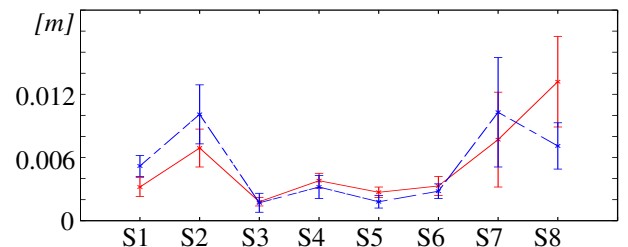


Fig. 8: Mean penetration and variance for each subject (Si) in taut (red) and slack mode (blue dash).

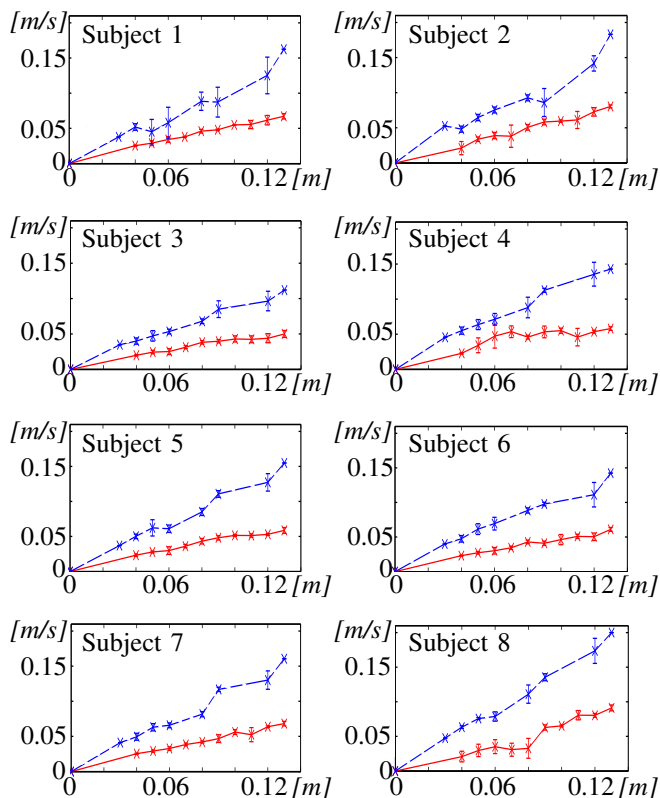


Fig. 9: Mean velocity and variance for each users depending on distance from the wall in taut (*red*) and slack (*blue dash*) mode.

The graph in Fig. 8 shows the mean value of penetration for each user during the contact in both modes. This penetration is directly proportional to the rendered contact force. Results show no relevant difference between slack and taut modes. They also indicate a high variability for each subject. On the contrary, velocity graphs in Fig. 9 clearly exhibit a higher velocity when cable are slacked. This also seems linked to the initial distance from the wall.

To evaluate how the control mode influences the perception, subjects were asked following questions to which they had to answer by red, blue, both or none. Questions marked with * had to be justified. These were :

- before the contact :
 - (a) which condition produces most vibrations?
 - (b) which condition gets unnecessary strained forces?
 - (c) which was the easiest condition to follow the path, the most fluent?*
 - (d) which condition seems more realistic?*
- at the contact :
 - (e) which condition presents the hardest wall?
 - (f) which condition produces the most vibration?
 - (g) which is easier to take away from the wall (less sticky)?
 - (h) which condition seems more realistic?*

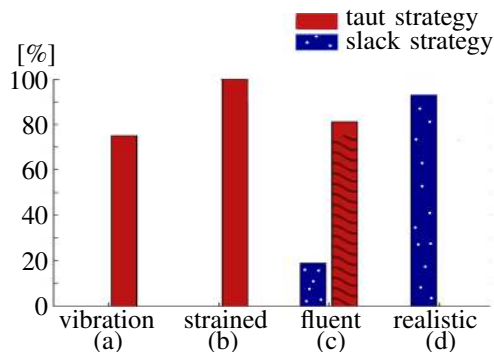


Fig. 10: Percentage of people who perceive the different characteristics presented in the questionnaire in the taut (*red*) or the slack (*blue*) mode in free exploration.

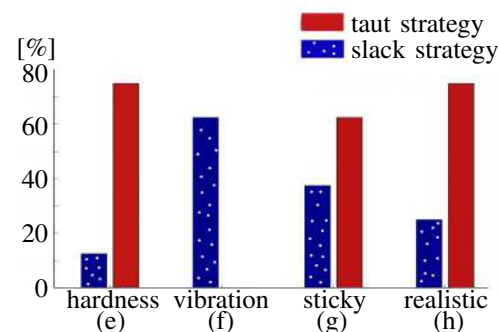


Fig. 11: Percentage of people who perceive the different characteristics presented in the questionnaire in the taut (*red*) or the slack (*blue*) mode when in contact.

In both cases, results are visible on bar charts showing the percentage of subjects who perceive different characteristics in taut method (*red*) or/and in the slack (*blue*).

According to the free exploration chart (Fig. 10), parasite forces such as vibration and strain are null with slack cables. As wires are constantly under tension in the taut mode, even if the static equilibrium is perpetually assured there is a clear sensation of augmented inertia or viscosity. On the contrary, for the manageable criteria, 81 % of people preferred the taut approach, whereas only 19% has chosen the slack mode. Interestingly, following a guide line seems helped by an apparent superior inertia. 75% of subjects (hatched part of the bar (c)) indeed confirmed to feel more stable and appreciated being guided when a precise path must be followed.

At contact, the second bar of Fig. 11 clearly indicates that 75 % of the subjects find the wall harder in the taut mode. The single opposing subject argues for vibrations. Indeed, more than 60% feels vibrations in taut mode when wires are blocked at once, what we call the *whip effect*. The difficulty to detach from the wall after the contact is represented by the stickiness of the wall. This perception is connected to the apparent inertia. Even if the taut method appears for the majority more sticky, the difference with the slacked control is not relevant given the number of subjects.

E. Analysis

As expected, slacking cables prevent the transmission of mechanical parasite effects. As users are completely free of external forces, they execute quicker motions. This shows clearly when distance to the wall is longest: the velocity is three times higher compared to the taut mode. Nonetheless, when asked to follow a specific path, the majority appreciate the stability provided by strained wire. The apparent inertia act as a filter to prevent involuntary motion of the hand.

The rendering of the contact by the slack running out is much closer to an impact. A stronger perception was therefore expected. However, most users showed a clear preference for the taut mode, although the simulated rigidity is identical in both cases. An analysis users' description of the impact shows that in slack mode the contact felt either as an elastic or tilted wall. It can be explained by the presence of a *funnel effect*: When participants approach the contact point, slack lengths get shorter and the relaxed working space reduces to a funnel. Even if the user goes for a contact point different from the one advised initially, slack lengths are not updated during the experiment. Therefore, the slack ran out on one cable before the other one. As a result, the initial force felt by the users were in this cable's direction, instead of along the wall normal during a very short instant prior to contact. This apparently was enough to deteriorate the apparent rigidity of the wall. Notably, the experimenter, placed by the side of the subject during the tests, noticed that most users failed to follow the shown path leading to predefined contact point. This *funnel effect* can explain the two mis-perceptions of the wall, as a tilted or soft surface. Interestingly, these effects are not interpreted by subjects as drawbacks but rather as intended and realistic stimuli. Nevertheless, even if some particular sensation can be provoked from this effect, this is not reliable enough.

V. DISCUSSION AND FUTURE WORK

A haptic interface is designed with cable transmission to avoid the creation of inertia, friction and vibration. To limit further the parasitic mechanical effects felt by the user, a new strategy to completely disconnect the user from the device is proposed by slacking the cables. A pilot experiment assessed the qualities and weaknesses of this approach. As expected, the free exploration case is apparently more transparent as no external forces are felt by the user. On the other hand, the rendering of impact is deteriorated because the estimated contact point, hence slack lengths, were predefined and not updated during the task. The transition to contact from free space requires a control scheme which would ensure that all cables would be taut quite simultaneously to minimize the *funnel* effect. This regulation must be implemented in real-time using an efficient position sensing of the handle in conjunction with a good prediction of the contact point, which is quite challenging in a real 3D case. It would be also interesting to evaluate the acceptable delay between different contributing cables in the perception of force direction.

Most of the results presented here come from a qualitative perception survey. Even if the potential effects were guessed in advance, their implication on real perception were not. An extended study can be done based on these observations. In particular, a precise measure of vibrations through accelerometers can be performed so they can be quantified and avoided.

A point can be raised concerning the gain in perception compared to complexity of the method. Fluency of the free motion mentioned above will surely have positive after-effect on manipulation and user energy consumption. The totality of our subjects indicated a preference for the slack mode arguing this advantage, giving that the contact is properly rendered. This correlates well with the friendliness in human machine interface and invite us to continue our investigations.

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