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Internal dissipation in passive sampled haptic feedback systems

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***Abstract*— In this paper the passivity algorithm proposed in [12] is revisited. This algorithm generates passive haptic feedback by monitoring the energy flows in the virtual environment. The original formulation of the algorithm could not deal well with large internal dissipation and high sampling frequencies. An alteration is proposed on how internal dissipation is handled. This alteration improves the robustness of the algorithm for a wider range of parameter values and sample times. The improved version of the algorithm is demonstrated in a virtual wall experiment.**

I. Introduction

The advent of medical robotics in the 1990's has greatly increased the attention towards haptic feedback devices and control algorithms. Haptic feedback devices are devices which couple the user bidirectionally to either a virtual or remote environment. A coupling is made between the user's movement and the reflected force in the case of impedance type devices and between the user's exerted force and the resulting movement in admittance type devices.

It is expected that surgical robots capable of delivering haptic feedback can be applied in a wide range of scenarios. These scenarios include (but are not limited to) advanced simulators [1], local assistive manipulators [7] and telemanipulation devices [2]. In the interaction with virtual environments the haptic feedback increases the realism of the interaction and thus the immersion of the user into the virtual environment. For telemanipulation applications haptic feedback can be used to increase the perception of the user of the remote interaction between manipulator and environment. Haptic feedback in surgical applications thus aims to improve the perception of the surgeon of the surgical site and to increase the accuracy and safety of the procedure.

One of the major research topics in this field deals with the stability of the haptic interaction between the user which operates in continuous time and the virtual environment/control algorithm which is implemented in software and thus executed in discrete time. It is well known that stability problems can arise due to the generation of "virtual" energy in this interconnection of the continuous and discrete domains [4].

This problem can be handled by designing the controller in such a way that no "virtual" energy can be generated, or that when it is generated it is properly dissipated. In [11] and [12] it was shown that this "virtual" energy can be determined precisely a posteriori for impedance type displays. A "bookkeeping" algorithm was presented with which continous time passive model could be implemented in a discrete manner maintaining overall passivity. The original formulation of this algorithm however has some boundary conditions with respect to the dissipation elements which can be included in the virtual environment in relation to the sampling frequency.

In this paper a change of the original algorithm is described that alleviates those boundary conditions. In section II we will first briefly discuss the passivity condition and several passivity perserving algorithms. In Section III port-based models are shortly described. In section IV the algorithm proposed in [12] is treated and the boundary conditions are explored. In section V a change of the original algorithm is described that alleviates those boundary conditions. Finally in section VI an example and experimental results will be demonstrated. The paper ends with conclusions and a discussion of future work in sections VII and VIII.

II. Virtual Environments & Passivity

The basic sketch of an impedance type haptic feedback system is depicted in Fig. 1. The user imposes a motion on the mechanical structure of the haptic interface, $v_r(t)$. This motion is sampled by the controller, $v_d(\bar{k})$ and based on the virtual environment an appropriate force feedback is computed, $\tau(\bar{k})$. By means of a Zero Order Hold (ZOH) operation the appropriate force, $\tau_r(t)$, is applied by the actuators in the haptic interface and fed back to the user until the next sampling instant.

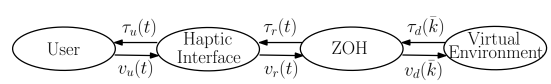

Fig. 1. Impedance type haptic feedback system

A system is said to be passive [10] when the energy which can be extracted from the virtual environment is bounded by the energy which was previously injected by the user. Passivity is a sufficient condition for stability, eq. 1, and is as such a desirable property.

$$\int_{t_0}^{t} -\tau_u v_u dt \geq 0 \quad (1)$$

In eq. 1 the positive energy flow is directed into the virtual environment.

In [11] it was shown that for impedance type displays the energy exchange between the continuous and discrete domain during a sample period T can be exactly determined as:

$$\begin{aligned} H_I(k) &= -\int_{(k-1)T}^{(k)T} \tau_r(t) v_r(t) dt \\ &= -\tau_d(\overline{k}) \int_{(k-1)T}^{(k)T} v_r(t) dt \\ &= -\tau_d(\overline{k})(q(k) - q(k-1)) \\ &= -\tau_d(\overline{k}) \Delta q(k) \end{aligned} \quad (2)$$

where $q(k)$ is the measured position of the haptic interface and Δq indicates the change in position in the past sample period. The index k refers to the value at the k^{th} sampling instance and $\overline{k}$ to the value which was computed at time instant $k-1$ and applied during the period $\overline{k}$ running from time instant $k-1$ to k.

The passivity condition can thus be expressed as:

$$\sum_{k=1}^{n} H_I(k) \geq 0 \quad (3)$$

Several algorithms use this formulation to guarantee passivity of the system. The PO/PC structure, described in [9], for instance monitors the balance of the energy exchange and employs when necessary a modulated viscous damper to regain passivity. In [5] upper and lower limits on the allowable change in applied force between samples are derived to limit the generated energy to the dissipation capacity of the physical interface itself.

These algorithms however only monitor and act upon the energy exchange through the interaction junction between the continuous and discrete domain without taking the virtual environment into acount. They ensure that the energy that can be extracted from the virtual energy equals the energy that was injected. As such they do not regard the enery which should have been dissipated due to internal dissipation. This means that when a virtual environment with internal dissipation starts to generate "virtual" energy, those algorithms will not activate until the generated "virtual" energy exceeds the internally dissipated energy and even then will only compensate for the excess between the two. A worst case scenario is that a virtual model consisting of a parallel spring and damper will feel like a solitary spring under certain conditions. This indicates that it is possible that although the interaction is stable the realism, and thus the usefulness, of it is diminished or even lost.

One of the strong points of the algorithm presented in [12] was that it introduced the concept of monitoring the energy flow throughout the entire virtual model. The energy that is dissipated internally, H_R in the virtual environment can thus be monitored and a stronger constraint can be placed on the passivity condition:

$$\sum_{k=1}^{n} H_I(k) \geq H_R \quad (4)$$

III. PORT-BASED MODELS

Port-based models are centered around the idea of energy exchange, e.g. Port-Hamiltonian systems [12] and Bond Graphs [8]. Any physical system can be described by a certain combination of energy converting, energy storing and/or energy dissipating elements which are connected by means of a power perserving structure. The elements are connected to this structure by means of power ports which are described by two variables whose product is power, in mechanics these variables are forces and velocities. The behavior of each element is described by a constitutive relation.

A Port-Hamiltonian system is composed of a state manifold χ, an energy function $H : x \rightarrow \mathbb{R}$ which expresses the total energy present in the system as function of the state x and a state dependant network structure $D(x)$. The general form of a Port-Hamiltonian system is graphically depicted in Fig. 2, where C are the storage elements, R represents the dissipation elements, $D(x)$ is the state dependant network structure that represents how energy is flowing through the system and energetic interaction ports to the external world and/or other Port-Hamiltonian systems are depicted.

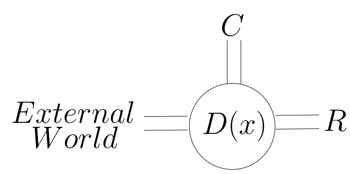

Fig. 2. Generic form of a port-based model

In continuous time the application of the incoming power port variable and the current state of the system on the Port-Hamiltonian system will result in the instantaneous value of the dual power port variable. The model of the environment with which the user is interacting through the haptic interface is however running in discrete time on a controller. This means that one of the power port variables is sampled and the other is held constant between samples. A direct implementation of the continuous time Port-Hamiltonian system in a discrete time can therefore result in energy being generated in the interconnection between the continuous and discrete domain and an associated loss of passivity.

In [12] it was already discussed that a passive discrete Port-Hamiltonian system can be realized by properly evaluating at each sample instant the energetic interaction that occured during the previous period between the continuous and discrete domain. The exchanged energy can then be properly distributed through the system.

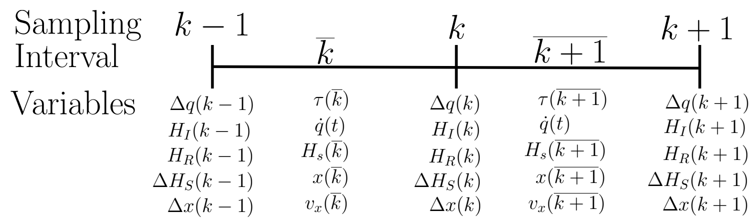

Fig. 3. Variable definitions used in algorithm

IV. Original Algorithm

In this section we will summarise the working of the original algorithm. As before the index k is used to indicate instantaneous values at the sampling instant k and the index $\overline{k}$ is used to indicate variables related to an interval between sampling instants k and $k-1$. The variables which are used are depicted in Fig. 3 and their meaning will be explained. In the rest of this paper we will focus on how the dynamic behavior of the virtual environment is computed in discrete time and we will refer to the state of the virtual environment simply as the state.

Suppose that at time instant $k-1$ a state change of $\Delta x(k-1)$ occured and the new state $x(\overline{k})$ resulted in the force $\tau(\overline{k})$ to be applied to the haptic interface by the ZOH during the time interval $\overline{k}$. The discrete "velocity" v_x of the system during the period $\overline{k}$ is computed by considering the state change that was computed at time instant $k-1$

$$v_x(\overline{k}) = \frac{x(\overline{k}) - x(\overline{k-1})}{T_s} \tag{5}$$

At the next sampling instant k the energy exchange between the continous and discrete domain during this time interval can be determined by evaluating the constant applied force and the change in position of the haptic interface, $\Delta q(k)$, according to equation 2. Assuming that the dissipative elements in the virtual environment are viscous elements, the energy that was supposed to be dissipated during the previous period is described as:

$$H_R(k) = T_s v_x^T(\overline{k}) R v_x(\overline{k}) \tag{6}$$

where R is the matrix containing in the damping coefficients.

The change in stored energy, $\Delta H_S(k)$ can now be computed by subtracting the dissipated energy from the interaction energy and a new value for the state, $x(\overline{k+1})$ can be computed that corresponds to the new stored energy, $H_S(\overline{k+1})$:

$$\begin{aligned} \Delta H_S(k) &= H_I(k) - H_R(k) \\ H_S(\overline{k+1}) &= H_S(\overline{k}) + \Delta H_S(k) \\ H_S(\overline{k+1}) &\rightarrow x(\overline{k+1}) \end{aligned} \tag{7}$$

This implementation however is in a sense in contradiction to the essence of the approach. The approach the algorithm advocates is that the energy exchange is evaluated a posteriori and that the energy balance is updated consecutively. What happens in this particular implementation is that the energy dissipation for the coming period $\overline{k}$ is fixed a priori at time instant $k-1$ based on the discrete "velocity" at that sampling instant. This creates problems when higher dissipation coefficients are introduced and higher sampling frequencies are used.

Fig. 4 and Fig. 5 show for instance the one dimensional contact responses by a simuluted user trying to execute a sinusoidal motion with a virtual wall located at q = 0 implemented by the above algorithm. The wall is simulated as a parallel spring and damper combination with a springconstant of $100N/m$ and a damping coefficient of $5Ns/m$. Fig. 4 shows the contact response when the sampling frequency is 40 Hz and Fig. 5 when the sampling frequency is set as 100 Hz. It is clearly visible that the higher sampling frequency leads to an incorrect display of the virtual wall.

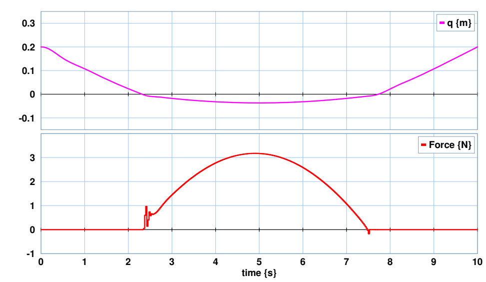

Fig. 4. Virtual wall simulation at 40 Hz

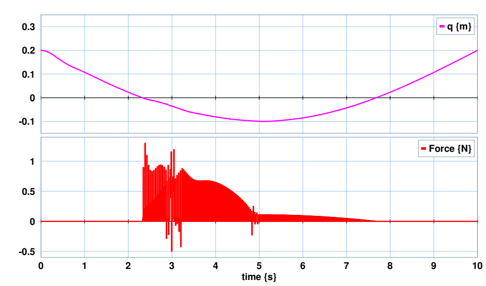

Fig. 5. Virtual wall simulation at 100 Hz

The cause for this problem is that it can happen that in the initial contact phase, the a priori calculated energy to be dissipated exceeds the energy which was injected into the virtual environment. The stored energy will then decrease instead of increase. Higher damping coefficients are problematic because when more energy is dissipated this problem is more likely to occur. Higher sampling frequencies are problematic because when the sampling time decreases the energy exchange decreases and the problem is again more likely to occur.

V. Proposed algorithm

The previous section showed that the method of handling internal dissipation in the virtual environment should be altered. In this section first the proposed alteration to the original algorithm is discussed after which the complete algorithm structure is presented.

A. Internal dissipation

There are two major situations: Energy is flowing from the continuous domain into the virtual environment, or energy is flowing from the virtual environment into the continuous domain. In the first situation part of the incoming energy has to be dissipated in accordance with the dissipative elements in the virtual environment and the remaining energy is stored. In the second situation an additional amount of energy has to be determined that is supposed to be dissipated. The combination of that dissipated energy and the interaction energy is then withdrawn from the stored energy. It can however happen, depending on the model, that close to the equilibrium position of the system the energy flows differ a little. For a virtual wall for instance consisting of a parallel spring and a regular viscous damper energy from the continuous domain has to be injected into the virtual wall to break the contact, this is known as the "sticky effect". These situations can be identified and properly handled when they occur.

In the original algorithm the stored energy could decrease when the user was injecting energy into the virtual environment. This can happen as the internally dissipated energy is independent of the injected energy. The dissipated energy was determined a priori based on the discrete "velocity" on that time instant, the assumption is that this "velocity" stays constant during the coming period. This however omits that there is a relation between the discrete "velocity" of the system and the state change which occurs at the end of the period. The dissipated energy should therefore be determined a posteriori. This means that whereas the original formulation had an update rule to choose a new state corresponding to the new energy level, in this new approach a state change has to be computed that satisfies:

$$\Delta H_S(\Delta x(k)) = H_I(k) - H_R(\Delta x(k)) \tag{8}$$

This means that like in the interconnection between the continuous and discrete domain the application of a force and the evaluation of the energetic effects of that force are seperated in time. If the dissipating elements in the virtual environment are viscous then the damping force which is applied during period $\overline{k}$ is computed at time instant $k-1$ based on the discrete "velocity", v_R, at the power port of the dissipative elements of the system at that time. That "velocity" can be related to the computed state change by means of the network structure $D(x)$.

$$\begin{aligned} v_x(\overline{k-1}) &= \frac{\Delta x(k-1)}{T_s} \\ \tau_R(\overline{k}) &= -v_R^T(\overline{k-1})R \end{aligned} \tag{9}$$

A constant discrete "velocity" of the system during the period $\overline{k}$ is then assumed and the energy which is dissipated during that period will be:

$$\begin{aligned} H_R(k) &= -\tau_R(\overline{k})v_R(\overline{k})T_s \\ &= -\tau_R(\overline{k})f(\Delta x(k)) \end{aligned} \tag{10}$$

where $f(\Delta x(k))$ expresses the discrete "displacement" of the dissipative power port as function of the state change based on the network structure $D(x)$.

This approach will approximate the continuous time dissipation when the sampling frequency increases:

$$\begin{aligned} \lim_{T_s \downarrow 0} \sum_{k=1}^{n} H_R(k) &= \lim_{T_s \downarrow 0} \sum_{k=1}^{n} v_R^T(\overline{k-1}) R v_R(\overline{k}) T_s \\ &= \int_{t=0}^{nT_s} v_R^T(t) R v_R(t) dt \end{aligned} \tag{11}$$

When energy is being injected by the user into the virtual environment a solution will always exist for the energy balance given in equation 8. The state change simply specifies which part of the energy is dissipated and that the rest is stored. When the energy flow is reversed however it is possible that an exact solution to this formulation of the energy balance does not exist. This problem is due to the ZOH operation. The applied force is held constant during the sampling period whereas in the continuous system when the user is extracting energy from the virtual environment the applied force immediatly decreases. The user extracts thus more energy during this time period from the discrete system than would be the case with a continous system and at the next sampling instant a state change that satisfies the energy balance cannot be found. When this happens an approximate solution can be found by reverting to the original formulation of the algorithm in which the dissipated energy is independent of the state change. For these situations this formulation of the dissipated energy is conservative as it is uses the discrete "velocity" of the system during the previous time period which is lower.

B. Flowchart

In the section above it was shown that the algorithm consists of several steps. In order to better depict its working, a flowchart of the entire algorithm for a contact task is given in Fig. 6.

1) Deadlock:

The above presented energy exchange based algorithm only works when the user and the virtual environment are indeed exchanging energy. This poses a problem when the user can switch between contact and free motion phases in the virtual environment. In order to push the virtual environment from this deadlock situation a first order approximation of the virtual environment is used when the user switches from a free motion to a contact phase. This generates a known amount of "virtual" energy which is recorded by the bookkeeping algorithm and later properly dissipated.

2) Passivity recovery:
The bookkeeping algorithm monitors the generated "virtual" energy and needs to properly dissipate this surplus energy. Any number of techniques can be applied here. An effective method is to use a modulated viscous damper which was originally proposed for the PO/PC structure [9]. Such a modulated damper gently extracts additional energy from the user to compensate for the generated "virtual" energy.

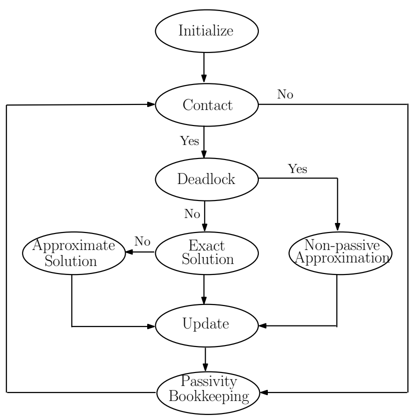

Fig. 6. Flowchart algorithm

VI. Example

The above described algorithm is worked out for a one dimensional virtual wall modelled as a parallel combination of a linear spring and viscous damper with springconstant k_1 and damping coefficient d_1. First the algorithm for this particular virtual environment is described and then experimental results are presented.

A. Virtual Environment

When the user is in contact with the virtual wall this is indicated by the condition

$$q(k) < q_w \tag{12}$$

In this particular example the discrete "velocity" at the dissipative power port equals the discrete "velocity" of the storage power port, so:

$$v_R(\overline{k}) = v_x(\overline{k}) = \frac{\Delta x(k)}{T_s} \tag{13}$$

If the system is in a deadlock situation the penetration into the virtual wall is taken as the state change of the virtual environment and as a result an amount of virtual energy H_{dis} is generated. This generated energy is to be dissipated by the bookkeeping algorithm.

$$\begin{aligned} \Delta x &= q - q_w \\ x &= \Delta x \\ \dot{x} &= \frac{\Delta x}{T_s} \\ \Delta H_{dis} &= \frac{1}{2}k_1 x^2 \\ \tau &= -k_1 x - d_1 v_x \end{aligned} \tag{14}$$

When energy is being exchanged between the continuous and discrete domain the proposed algorithm can be used. The exchanged energy, the change in stored energy and the dissipated energy are given by:

$$\begin{aligned} H_I(k) &= -\tau(\overline{k})(q(k) - q(k-1)) \\ \Delta H_S(k) &= H_S(\overline{k+1}) - H_S(\overline{k}) \\ &= \frac{1}{2}k_1(x(\overline{k}) + \Delta x(k))^2 - \frac{1}{2}k_1 x(\overline{k})^2 \\ &= \frac{1}{2}k_1(\Delta x(k))^2 + k_1 x(\overline{k})\Delta x(k) \\ H_R(k) &= d_1 v_x(\overline{k-1})\Delta x(k) \end{aligned} \tag{15}$$

The state change that satisfies the energy balance is therefore given by the following quadratic equation

$$\begin{aligned} a(k) &= \frac{1}{2}k_1 \\ b(k) &= k_1 x(\overline{k}) + d_1 v_x(\overline{k-1}) \\ c(k) &= -H_I(k) \\ \Delta x(k) &= \frac{-b(k) - \sqrt{b(k)^2 - 4a(k)c(k)}}{2a(k)} \\ v_x(\overline{k}) &= \frac{\Delta x(k)}{T_s} \\ \tau(\overline{k+1}) &= -k_1 x(\overline{k+1}) - d_1 v_x(\overline{k}) \end{aligned} \tag{16}$$

when the "sticky" effect occurs, the user is moving out of the wall but injecting energy into the virtual environment, the other solution to the quadratic problem should be selected.

The existence of an exact solution is given by the condition

$$b(k)^2 \geq 4a(k)c(k) \tag{17}$$

If there exists no exact solution the approximate solution given by equations 6 and 7 is used until the energy stored in the virtual environment is depleted:

$$\begin{aligned} H_R(k) &= T_s v_x^T(\overline{k-1}) R v_x(\overline{k-1}) \\ H_S(\overline{k+1}) &= H_S(\overline{k}) + H_I(k) - H_R(k) \\ x(\overline{k+1}) &= \sqrt{\frac{2H_S(\overline{k+1})}{k_1}} \\ \Delta x(k) &= x(\overline{k+1}) - x(\overline{k}) \\ v_x(\overline{k}) &= \frac{\Delta x(k)}{T_s} \\ \tau(\overline{k+1}) &= -k_1 x(\overline{k+1}) - d_1 v_x(\overline{k}) \end{aligned} \tag{18}$$

In order to regain passivity a switched damping structure similar to the PC algorithm [9] is applied:

$$\begin{aligned} d_{pas}(\overline{k}) &= \begin{cases} \alpha H_{dis}(\overline{k}) & \text{if } H_{dis}(\overline{k}) > 0 \\ 0 & \text{otherwise} \end{cases} \\ \tau_{pas}(\overline{k}) &= -d_{pas}(\overline{k})\Delta q(k-1)/T_s \\ \Delta H_{pas}(k) &= -\tau_{pas}(\overline{k})\Delta q(k) \\ H_{dis}(\overline{k+1}) &= H_{dis}(\overline{k}) + \Delta H_{dis}(k) - \Delta H_{pas}(k) \end{aligned} \tag{19}$$

B. Experimental Results

The algoritm was implemented on a physical system. As haptic interface the Freedom 6S [6] was used. The algorithm is executed using the computer program 20-sim [3]. This software allows for soft real time simulation on a Windows based OS by introducing dynamic wait states. The achievable real time sample times are limited, but offers sufficient performance for the chosen parameter settings. Parameter settings for the virtual environment were: $k_1 = 100N/m$, $d_1 = 10Ns/m$ and $q_w = -0.05$.

Interaction experiments with the described virtual environment were carried out. One of the experiments was carried out using a sample frequency of 40 Hz and in the second experiment the sample frequency was increased to 100 Hz. The contact responses for both experiments are listed in Fig. 7 and Fig. 8. These figures show that with the new formulation of the internally dissipated energy a stable interaction with the virtual wall at both the lower and the higher sample frequencies is obtained. The "sticky" effect due to the linear viscous damper occuring at the end of the contact phase is also displayed.

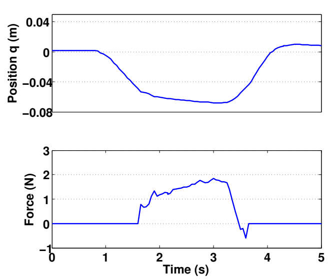

Fig. 7. Virtual wall experiment at 40 Hz

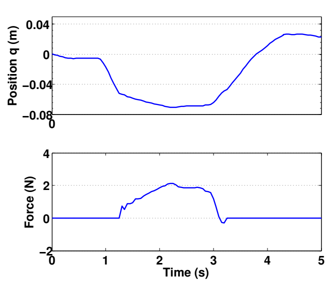

Fig. 8. Virtual wall experiment at 100 Hz

Fig. 9 shows the recorded interaction energy and internally dissipated energy for the second experiment. It is clearly visible that the stronger condition on the passivity condition of equation 4 is indeed achieved with this algorithm.

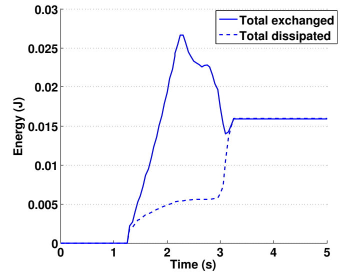

Fig. 9. Exchanged and dissipated energy

VII. Conclusions

The algorithm originally presented in [12] was revisited. An alteration was proposed with respect to the manner in which the internally dissipated energy is calculated. The results in section VI show that the new formulation is indeed capable of monitoring the internally dissipated energy and displaying a stable interaction over a wider range of parameter settings than the original algorithm. Using this algorithm a stronger condition on the passivity condition can be enforced allowing the correct and passive display of virtual environment which contain internal dissipation.

VIII. Future Work

One of the problems remaining is the need for a differentiation in the algorithm and the associated sensitivity to measurement noise. Future work will be directed towards decreasing this sensitivity of the algorithm.

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