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LATENCY EVALUATION AND MODELING OF A MECHATRONIC DISPLAY FOR TELEMATIC MUSIC

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ABSTRACT

Chamber musicians' bodily movements are important for coordination, synchronization, and expression, but low-latency systems for displaying performers' movement in telematic music performance remain elusive. Even if the challenges of low-latency video encoding and transmission could be overcome, prior research has shown that three-dimensional physical movement in space is more persuasive and compelling than a projected image of the same movement on a screen. We describe a system for capturing, transforming, and displaying telematic chamber musicians' movements through a non-anthropomorphic mechatronic avatar with seven degrees of freedom.

We experimentally quantified the movement-domain phase delays arising from the structural response of the mechatronic avatar, providing a bound on the latency contributed by our system, which determines how the performer's movement is transmitted and displayed to support embodied telematic performance. We assessed the avatar motion response to a step command issued to each of the avatar's servo motors using recorded avatar movements, and fit second-order models to characterize mode shapes and quantify phase delay. A comparison with audio-domain latencies provides an estimate of asynchronization and informs the future viability of infrared motion capture and mechatronic displays for networked music performances.

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1. INTRODUCTION

Telematic music is a form of network music performance in which musicians play together synchronously, in real time, from disparate geographic locations, supported by audio streamed over the internet [1]. A variety of specialized tools have since been developed for academic, professional, and home studio use [2].

The telematic medium supports a wide range of musical practices and styles [3]. Chamber music is generally well-suited to the constraints of the telematic medium. Chamber music involves a relatively small number of musicians, which minimizes the number of audio channels and corresponding bandwidth requirements, and the lack of a conductor makes coordination and synchronization more manageable. However, telematic chamber music performance can be confounded by latency. Latency can be understood as the time delay between the input and output of a system, or the time delay between an action and its intended effect. In telematic music, latency refers to "the delay between the moment a musician in one location makes a sound and the moment a second musician in a different location hears that sound" [4]. One consequence of this delay is that the combined sound of the local and remote performers will be different in either location [5]. Latencies on the order of tens of milliseconds have been demonstrated to impact musicians' ability to synchronize and maintain a stable tempo, with synchronous performance becoming difficult or impossible beyond around 65 ms [6, 7] (although some have placed the limit of performability somewhat higher [8]). Nonetheless, under conditions with acceptable latency, around 10-25 ms one-way, telematic musicians have demonstrated the ability to play synchronously with a steady tempo with only audio streaming between locations [2].

Most technologies for telematic music performance therefore understandably prioritize high-quality audio with low latency [9]. Consequently, visual communication has generally been viewed as ancillary in these contexts. Yet, chamber musicians performing in ordinary (co-present) conditions produce and exploit bodily movements beyond those that are strictly necessary for producing instrumental sound. These movements, both purposeful and incidental, are critical for coordination, synchronization, and expression [10, 11]. A substantial body of research has examined the role of gesture in instrumental music performance, with a number of efforts to categorize different forms or types of gestures and describe their role and impact on co-performers and audiences [12]. Some telematic musicians and performance systems have incorporated video in an effort to facilitate visual communication and gestural exchange [13]. In such systems, video is frequently subject to substantial latency, creating impediments to audiovisual synchronization and real-time performance. Video accumulates latencies in coding, transmission, decoding, and buffering. Even in teleconferencing technologies designed to minimize video delay for human discourse, latencies from 300ms to 1s accumulate, which fall outside the transmission speeds needed to coordinate video with minimal latency audio [14].

A compelling body of research has examined the particular qualities of three-dimensional movement in space in comparison to two-dimensional screen-based displays. In particular, when displaying the same scale and quantity of information, three-dimensional mechatronic avatars were found to be more persuasive than screens [15], even when given a non-anthropomorphic form.

2. SYSTEM DESCRIPTION

We devised a system for peer-to-peer telematic performance by instrumental duos in two locations. The system is described in greater detail elsewhere [16].

2.1 Audio

A USB audio interface captures microphone input at each location. The open-source JackTrip software streams uncompressed 48 kHz / 16-bit audio between locations [17].

2.2 Motion Capture

Performers' movements in each location are captured by a Qualisys infrared motion capture system. Each performer wears a suit with reflective markers placed to provide an accurate skeletal model. Qualisys Track Manager (QTM) software on a dedicated PC provides 3D marker position and 6-DOF rigid-body data, streamed in real time as Open Sound Control (OSC) message bundles wrapped in UDP packets [18]. We transmit the QTM data on an Ethernet local area network to another Mac computer, where they are received in Cycling '74 Max. In Max, we compute motion descriptors from the movement data and map these to desired joint angles of the mechatronic display's seven motors. In a telematic performance, motor positions are streamed as bundles of OSC messages in UDP packets over the Internet to the distal location at a rate of 100 Hz. These messages are received in Max on a Mac computer in the distant location, and transmitted to the mechatronic display.

2.3 Mechatronic Display

The mechatronic display is inspired by the form and function of spring-balanced desk lamps [19], which are also immortalized in John Lasseter's Luxo Jr. ('The Pixar Lamp'). Luxo Jr. embodies the concept and practice in animation that a nonhuman topology can evoke humanlike qualities if its movements are animated appropriately [20]. With physical robots, studies have shown that nonhuman morphologies can remain evocative of human affect and agency through lively movement [21].

The display, illustrated in Fig. 1 consists of two linked arms that support a flower-like 'head'. The arms allow the display to compress and expand vertically and lunge forward, much like the body of Luxo Jr. The 'neck' connecting the head to the upper arm is 3D printed from flexible TPU and actuated with parallel motors and a custom linkage to give more organic movement than would be possible with a traditional pan/tilt configuration. The 'face' is an origami-inspired paper flower derived from open source designs [16]. The face is actuated by steel rods attached to oppositionally-paired horizontal and vertical servo motors near the neck. The resulting motion evokes the opening and closing of a flower head or the mouth of a hand puppet. The entire assembly is rotated by a large motor at the base of the lower arm.

There are 9 motors on the display, but the horizontal and vertical 'face' motors move in oppositional pairs, resulting in 7 distinct motor control data streams from the

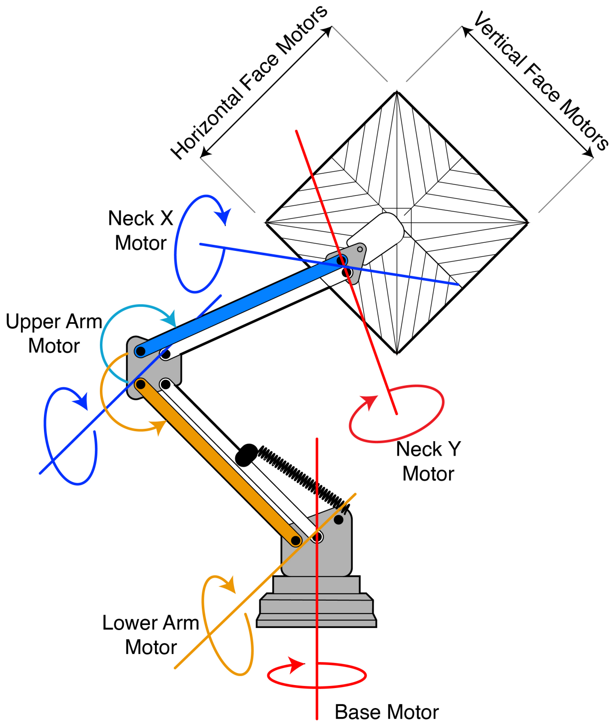

Figure 1. Mechatronic display, indicating motors and axes of rotation.

computer. Each motor control command is transmitted from the computer to the display as a 14-bit target position. These commands are transmitted as serial data over USB in 16-byte frames (14 data bytes plus start and stop bytes) every 10ms, at a serial baud rate of 115,200 bps. The display is driven by an Arduino Mega 2560 microcontroller that receives and parses the serial control data from the computer, and forwards the motor position commands to the motor controllers. The base and two arm motors are Dynamixel smart servos (MX-64AR and MX-28AR, respectively). A Dynamixel Motor Shield connected to the Arduino Mega interfaces with the motors via RS485. The motors that actuate the 'neck' and 'face' are EMAX ES08MA II analog servos, controlled by a PCA9685 PWM servo driver that interfaces with the Arduino via I2C.

2.4 Sources and Types of latency

We can broadly conceive of latency in two domains in our system: audio and movement. The one-way audio latency is the time it takes for sound generated by a local performer to arrive at the ears of the distant performer. Rofe and Reuben [4] define several contributing factors to this latency. Following Cáceres [17], we boil these down to four categories: **1)** ***Acoustic latency***: sound propagation time in air; **2)** ***Conversion latency***: time required at the hardware and operating system levels to convert between analog and digital signals and interface with applications; **3)** ***Application latency***: choices of audio quality, sampling rate, buffering, packetization, etc. in the streaming software; and **4)** ***Network latency***: transmission delays due to geographical distance, routing/switching, security, and network conditions.

With a microphone placed as close as possible to the performer and the distant performer wearing headphones, we consider *acoustic latency* to be negligible. *Conversion latency* is dependent on audio hardware and operating systems, but for reasonably high-quality consumer audio interfaces and general-purpose operating systems, end-to-end latency is generally considered to be on the order of 5 ms. [1] A recent analysis of dedicated telematic streaming applications found *application latencies* of around 10-30 ms [9], with the JackTrip software used in our experiments being at the upper end of that range. We therefore estimate the minimum audio latency in our system to be around 35 ms. With the type of network infrastructure typically available at university research centers, *network latency* will depend primarily on the geographic distance between locations. In our recent performances between two US universities about 1000 km apart, we measured *network latency* of 20-25 ms using the *traceroute* utility [16], yielding a total audio latency of 50-60 ms.

The movement domain presents several different sources of latency. We categorize these as: **1)** ***Computational latency***: instances of computational complexity, primarily in computing motion capture marker positions. **2)** ***Local communication latency***: buffering, sampling, and communication rates of local systems. **3)** ***Phase Lag***: dynamic response of the mechatronic system. **4)** ***Network latency***: transmission delays, as above. In our system, motor control and audio data are both transmitted as UDP to computers on the same subnet in the distant location, therefore we assume *network latency* to be the same as in the audio domain.

[1] https://symonics.com/tested-soundcards/

3. EXPERIMENT

We devised an experiment to measure other sources of movement-domain latency in our system with the goals of: i) establishing a lower bound on the total movement-domain latency that we would experience in a telematic performance; ii) understanding the expected amount of asynchronization between audio and movement; iii) characterizing the temporal qualities of the movement of the mechatronic display.

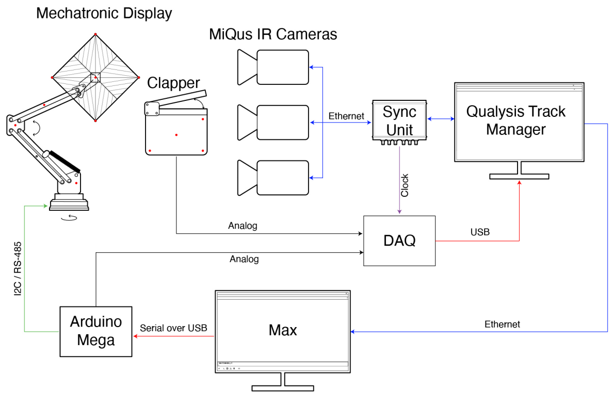

Figure 2. Experiment setup.

Asynchronization here is defined by the difference between total movement-domain latency and total audio-domain latency. We conducted the experiment with a local mechatronic display, effectively eliminating any Internet data transmission and *network latency*. The total movement-domain latencies encountered in our experiment are therefore attributable only to computation, local communication, and phase lag. Ideally, the sum of these would be similar to the corresponding 35 ms of expected audio-domain latency. We further wanted to isolate the phase lag, and arrive at a more nuanced understanding of the system's movement.

The experimental setup is shown in Fig. 2. We built a clapper with an electrical switch that closes when the clapper arm contacts the clapper body. When closed, the switch causes infrared LEDs on the body of the clapper to illuminate. Also simultaneously, a voltage step is generated on a BNC jack on the clapper. The clapper switch closure thus creates a simultaneous electrical impulse and optical trigger.

The electrical output of the clapper is connected to an analog data acquisition (DAQ) unit whose inputs are recorded synchronously to the motion capture data in QTM. Analog data are recorded in QTM at 1920 Hz, while optically tracked marker positions are recorded at 240 Hz. The recording captures several events in the human movement-to-display movement sequence. The timing of these events provide latency measurements at various stages of the system, which cumulatively amount to the total system latency. The instant the clapper switch closes becomes our reference time t_0. We assume zero latency between the electrical impulse and the time it is recorded in QTM, therefore we define t_0 as the QTM analog data frame where the voltage step is first detectable.

The infrared LEDs on the clapper are recognized as motion capture markers by the Qualisys system, and a predefined model for the fixed spatial configuration of the LEDs allows the system to recognize and label the markers. The marker positions are recorded in QTM and also streamed via Open Sound Control as UDP over the LAN to the computer that computes the motor commands. This data path is identical to the configuration used in our telematic performance configuration [16]. However, in this experiment, instead of streaming the computed motor commands to a remote location, the display is connected locally. The motor control software in Max and the Arduino firmware are reprogrammed such that for every trial, the first clapper marker position received in Max causes a predefined motor command data packet to be sent at the next data frame to the Arduino. The Arduino responds to the first motor command message it receives by instructing one motor to move to a predefined position, representing a step of roughly $\frac{1}{4}$ of the motor's total range of motion. Markers on the display allowed us to track the resulting movement of the display in QTM. The Arduino also toggles a digital output pin as soon as it receives the message from the computer, immediately before initiating the motor movement. The position of that motor is reset to the same initial position after each trial. We conducted three trials for each motor, 21 in total.

In summary, we recorded the following discrete data streams in QTM: 1) Analog voltage signal from the clapper. 2) Marker positions on the clapper. 3) Analog voltage signal from Arduino digital output pin, triggered when the first motor control command is received. 4) Marker positions on the mechatronic display.

4. ANALYSIS

For each trial, we analyzed the recorded data to measure the timing of four events after the recording started, shown in Fig. 3.

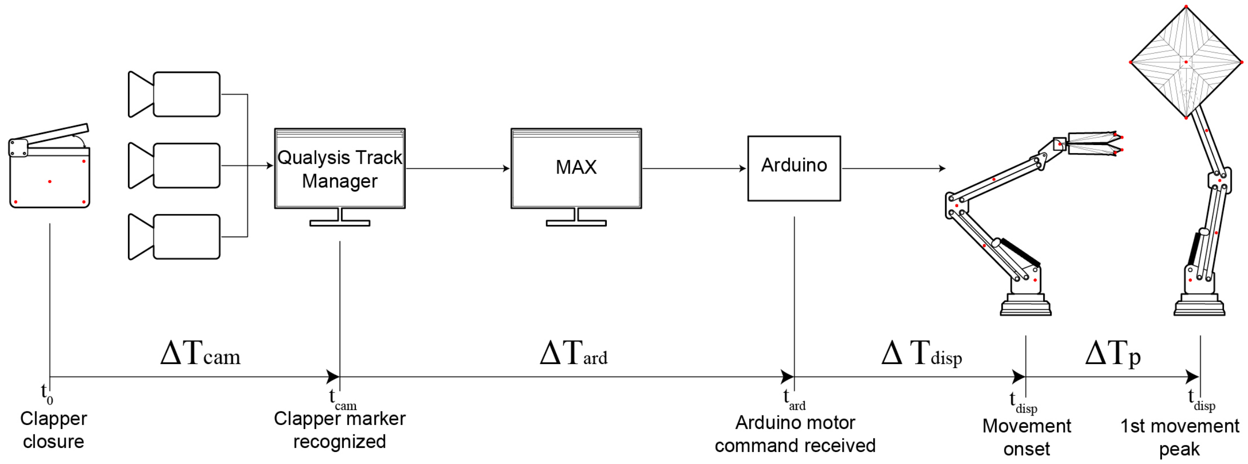

Figure 3. Timeline of events measured.

Table 1. Motor Response Characteristics

Motor Name	Amplitude A (mm)	First Peak $t_p - t_{ard}$ (s)	Dominant Period T (s)	Decay Constant τ (s)	Movement Onset $t_{disp} - t_{ard}$ (s)
1: Base	14.106 ± 0.226	0.156 ± 0.004	0.160 ± 0.010	N/A	0.081 ± 0.020
2: Lower Arm	44.598 ± 1.010	0.442 ± 0.003	0.456 ± 0.010	0.608 ± 0.105	0.067 ± 0.001
3: Upper Arm	86.130 ± 4.645	0.341 ± 0.003	0.424 ± 0.002	0.226 ± 0.002	0.056 ± 0.023
4: Neck X	34.907 ± 1.192	0.268 ± 0.033	0.464 ± 0.028	0.522 ± 0.021	0.052 ± 0.003
5: Neck Y	31.692 ± 1.977	0.205 ± 0.004	0.322 ± 0.009	0.360 ± 0.021	0.058 ± 0.003
6: Horizontal Face	16.278 ± 0.309	0.174 ± 0.002	0.251 ± 0.002	0.189 ± 0.011	0.043 ± 0.005
7: Vertical Face	22.405 ± 0.379	0.156 ± 0.006	0.222 ± 0.002	0.165 ± 0.019	0.041 ± 0.009

t_{cam}: The first clapper marker position is registered in QTM. The corresponding period ΔT_{cam} encompasses the *computational latency* incurred in recognizing the markers and computing their positions. There is likely a negligible *local communication latency* component due to the ethernet communication between the cameras, sync unit, and PC. The mean ΔT_{cam} over all trials was 3.323ms (SD 1.635), where much of the variance may be attributable to the frame rates of analog and mocap systems (1920 and 240 Hz respectively, corresponding to frame periods of 0.521ms and 4.167ms.

t_{ard}: The voltage step from the Arduino digital output pin, triggered by receipt of the motor command from the computer. $\Delta T_{ard} = t_{ard} - t_{cam}$ encompasses *local communication latencies* incurred by network transmission (including packetizing and decoding) of marker position data from QTM to Max and serial transmission (including encoding/decoding) of the motor command to Arduino. There is additional *computational latency* incurred by the calculation of the desired motor positions in Max. The mean ΔT_{ard} was 69.22ms (SD 92.90). The large standard deviation may be attributable to the presence of extreme outliers in five trials, as shown in Fig. 5. We suspect these are caused by processing queue overloads in Max due to the large stream OSC messages streaming from QTM. These may cause missed frames in the 100Hz timer controlling data to Arduino. After excluding outliers, the mean ΔT_{ard} was 26.43 (SD 5.131).

t_{disp}: Onset of movement as observed on the display, measured as the first moment in time where the marker has

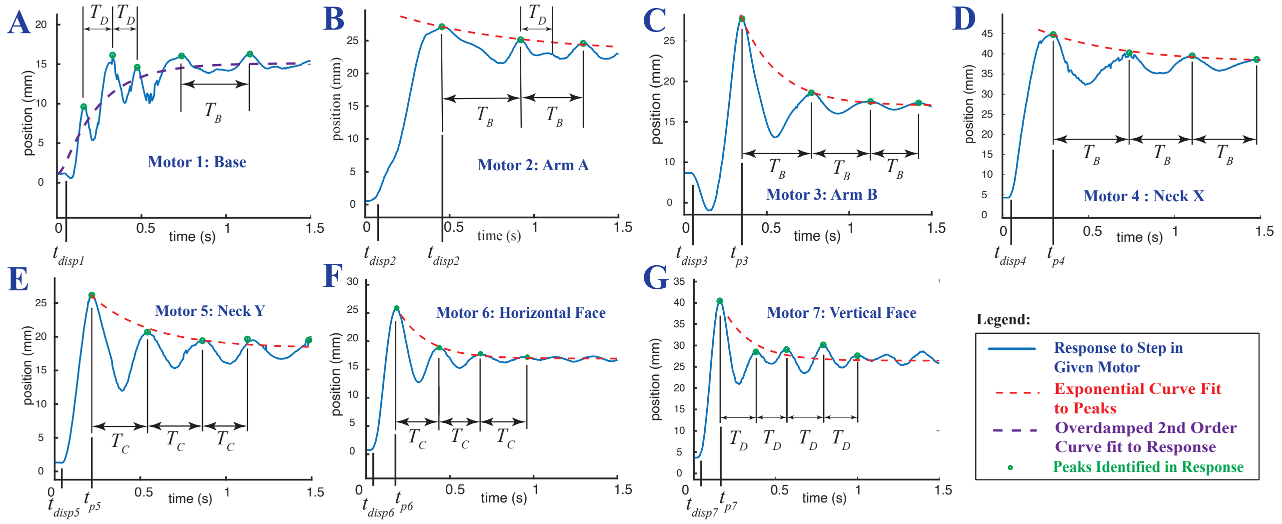

Figure 4. The response of Marker N (or marker E for Motor 6) to a step command in each of the seven motors is shown. Subfigures A through G show the response to a step command in Motors 1 through 7. The instant $t = 0$ in these plots corresponds to the event t_{ard} after the clapper close event.

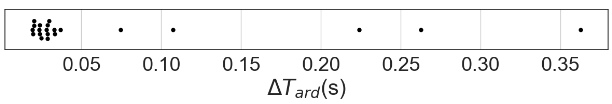

Figure 5. A swarm plot of ΔT_{ard} across all 21 trials.

moved at least 5% of the amplitude from its initial position at $t = t_{ard}$, where "5%" was an empirically determined number which strikes a good balance between accuracy and precision in the presence of sensor noise. As shown in Tab. 1, t_{disp} is on the order of 40 to 80ms and is quite significant. We note that the highest value of t_{disp} is for the base motor, which moves the most mass, and the lowest values are for the face motors which move the least mass.

t_p: Display reaches first "peak" of oscillatory motion, as shown on Fig. 4. The quantity $t_p - \Delta T_{disp}$ is nominally a half period of the dominant oscillatory motion.

For each recorded data stream pertaining to each motor, we identified the marker which consistently exhibited the largest movements among all markers on the mechatronic display, and limited our analysis to one axis (X, Y, or Z) of the said marker along which the projected motions were the largest. Fig. 4 shows a sample response for each of the seven motors in subfigures. From the peaks found in each step response, we identify in Tab. 1 the time elapsed until the first peak of the response, the period of oscillatory motion estimated by the time between the first two peaks, ΔT_{disp}, and the exponential decay constant of the oscillation peaks if deemed appropriate.

Assessing the responses, we recognize four dominant mode shapes, as shown in Fig. 4 and listed in Tab. 2. One dominant mode shape appears to be overdamped (non-oscillatory) while the other three are underdamped (oscillatory). The overdamped mode appears in the response to the base motor and is characterized by the time constants τ_1 =30ms and τ_2 =230ms, according to a rough curve-fit (see Fig. 4A). A first underdamped mode with a natural frequency of about $f_B = \frac{1}{2\pi}\omega_B$ =2.22Hz or period T_B =450ms is apparent in the responses to steps issued to the upper and lower arm motors (see Fig. 4). A second underdamped mode with a natural frequency of about $f_C = \frac{1}{2\pi}\omega_C$ =3.15Hz or period T_C =317ms is apparent in the responses to steps issued to the Neck Y and the Horizontal Face motors. A third and final underdamped mode with a natural frequency of about $f_D = \frac{1}{2\pi}\omega_D$ =5.13Hz or period T_D =195ms is apparent in the responses to steps issued to the Base, Lower Arm, and Vertical Face motors.

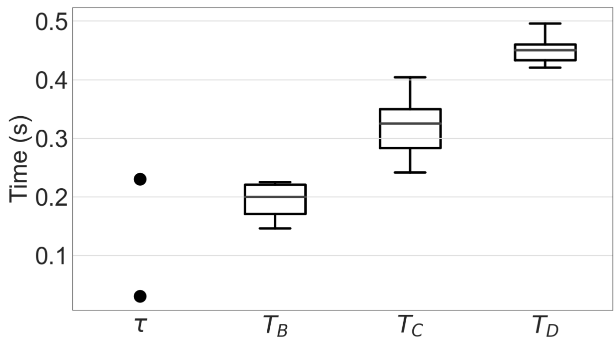

Figure 6. Measured oscillation periods T and time constants τ grouped by mode.

Table 2. Time constants associated with overdamped mode and periods associated with oscillatory modes.

Mode	Characterisitc	Mode Period (ms)
A	overdamped	$\tau_1 \simeq 30, \tau_2 \simeq 230$
B	underdamped	$T_B = 450 \pm 20.9$
C	underdamped	$T_C = 317 \pm 43.3$
D	underdamped	$T_D = 195 \pm 27.3$

5. DISCUSSION

Our experimental determination of the local communication and processing latencies and our ad hoc modal analysis of the mechatronic display allow us to quantify two major contributions to latency that a musician will experience using our prototype device to support telematic music performance. These contributions add to the network latency incurred in Internet transmission, and together all movement-domain latencies inherent to use of the mechatronic display may be compared to the audio-domain latencies to estimate the degree of asynchronization in our application. Cumulatively, we encountered movement-domain latencies on the order of 70-100ms from the moment of impulse into the system to the onset of movement in the display ($\Delta T_{cam} + \Delta T_{ard} + \Delta T_{disp}$). This is roughly 2-3x the expected audio-domain latency. These results point to possible improvements in our system architecture. We note in particular that ΔT_{ard} could likely be substantially reduced by performing mocap-to-motor control mapping on an embedded device instead of a PC.

Further, results of our ad hoc modal analysis inform both the design of the mapping from human gesture to motor commands and the design of a next generation mechatronic display. Naturally, the interpretation of the modal analysis results requires a consideration of the distinction between the *phase lag* of a dynamical system and the *latency* associated with communications. Whereas latency is a "pure delay" corresponding to a transmission or transport delay that does not vary with the frequency content of the transmitted signal, phase lag imparts a delay on each frequency component of a signal according to the frequency of that component. For a second order system (the chief characteristic of a mass attached to ground through a compliant structure) a phase lag between 0° and 180° will be imparted, with 0° for frequency components well below the natural frequency ω_n and 180° for frequency components well above ω_n. Frequency components at ω_n will experience 90° phase lag. The quantity 90° corresponds to a time delay of $T/4 = \frac{1}{4}\frac{2\pi}{\omega_n}$. That is, an excitation at ω_n will produce a delay roughly equivalent to a quarter period. For example, an excitation at the lowest underdamped frequency $f_B = 1/T_B = 1/0.450s = 2.22Hz$ will produce a 90° phase delay or $\frac{1}{4}0.450s = 0.112s$.

The frequencies corresponding to the periods in Table 2 of the three underdamped mode shapes that we identified are 2.22, 3.15, and 5.13 Hz—certainly frequencies that a musician can produce, though usually with fingers, hands, and the more distal body parts. Gestures of the head, arms, and body are likely in lower frequency ranges. Gestures produced by a musician, tracked and transmitted by motion tracking technology, mapped to certain motor commands, and issued to the motors in the mechatronic display are likely to be met with phase lags on the order of quarter periods and up to half periods of the mode shapes we found. The lower frequency content of larger gestures, however, will be met with lower phase lags. Moreover, modes present in the mechatronic display that are lightly damped will oscillate in response to excitations with significant spectral power at or above the corresponding frequency. If such oscillations are not present in the musician's motion that generated the excitation, such oscillations must be considered unintended artifacts of the mechanical realization. Re-design of the mechatronic display could involve adjustment to structural stiffness, damping, and mass distribution properties or more powerful motors accompanied by control system tuning. In the end, mode shapes that better reflect the speed (frequency) and damping of the human body in its various joints from proximal to distal will likely produce the best effects. Concomitantly, a mapping of motions from human to mechatronic avatar can be considered a design feature to be varied to minimize artifacts.

6. ACKNOWLEDGMENTS

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