

ExPRESSO : Perceptual Scheduling for Embedded Systems

César Torres

Department of Electrical Engineering and Computer Sciences
University of California Berkeley
cearto@eecs.berkeley.edu

ABSTRACT

Actuators in embedded systems are conventionally used in simple, yet limited ways — usually bound to a binary state or mapped to a sensor value. However, there exists a wide design space that can enhance a system's ability to communicate to a user. As more Internet of Things devices enter this landscape, the ability to control several actuators is limited by both the performance constraints of the embedded system and the current scheduling routines which require precisely timed signals for each actuator in the system. We introduce the ExPRESSO Perceptual Scheduler (**EPS**), a mechanism which factors in the different mechanical, perceptual, and software (MPS) profiles of actuators within a system to produce perceptually accurate and synchronous output. We show how **EPS** is able to operate on a portion of system bandwidth and still maintain the quality of service of its perceptual tasks while degrading gracefully under oversubscription.

Author Keywords

Scheduling, Internet of Things, perception

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI):
Miscellaneous

INTRODUCTION

In physical computing, tasks which require physical output to convey information, which we term behaviors, are subject to a different type of constraints than traditional software tasks. These types of tasks are subject to both mechanical impedances of the actuator mechanisms as well as discrepancies between physical stimuli and the human perceptual system. In this paper, we show how this is further complicated when systems are required to control actuation of several modalities (light, heat, angle, vibration) at scale.

Behaviors have already been shown to be incredibly successful at conveying system state [4, 9]. Such examples include Huppi et. al. patented “breathing” status LED indicator used in modern Apple computers [6], or the 8-bit sound aesthetic

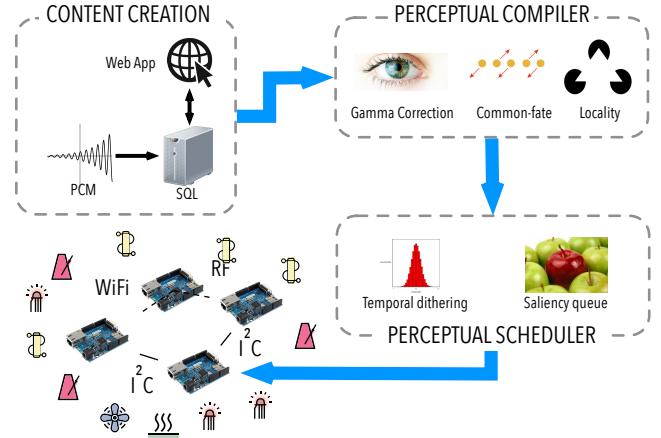


Figure 1. The ExPRESSO pipelines consists of a content creation stage with stores content in a SQL db. This is then called-on-demand by the scheduler, where it is then compiled and sent as actuation tasks to micro controllers in a actuator system, who then handle routing commands to the appropriate actuators.

from early gaming systems [8]. However, as the number of distributed wireless-addressable actuators in the Internet of Things (IoT) increases, e.g., Phillips Hue lights, new types of *distributed* behaviors arise, or behaviors which take into consideration the environment and each other, rather than operating as point-based designs.

Developing distributed behaviors can enable ambient display technologies, such as ambientROOM, an environment which uses ambient media – ambient light, shadow, sound, airflow, water flow — to communicate information in the cognitive-background, opening a new interaction space where users can transition between background and foreground information [7]. Furthermore, controlling distributed actuators at scale has been shown to enable ad-hoc display technologies. For instance, Schwarz et. al. demonstrates how localizing cell phone screens in a scene and controlling their output can be used to construct large collective displays in situations like sporting events, concerts and political rallies [11]. Heaton similarly shows how distributed devices disrupt the current paradigm of “matrix’ed” displays, and redefine control of both a pixel (data structure) and the physical pixel (visible form)[5].

This vision however is currently limited by performance constraints (I/O-bound) of embedded systems and current scheduling routines which require precisely timed signals for

each actuator in the system — restricting the scalability of the system. Furthermore, for a distributed actuator system (DAS), every node has a different performance profile and network latency, which make coordinating behaviors especially difficult [2].

These issues are currently mediated through hardware optimizations. For example, LED drivers use a shared common hardware line and multiplexed signals to drive multiple LEDs in parallel. This takes advantage of driving a single common actuator, and foregoes the complexities of controlling systems with multiple actuators. Recent advancements in LED driver firmware such as Fadecandy [12] circumvent creating precisely timed signals by using perceptual optimizations such as dithering and color correction. However, hardware-centric techniques, while powerful for controlling large sets of connected actuators, are bound by the physical constraints of hardware lines.

Currently within embedded systems, software-controlled behaviors are interrupt-driven, a preemptive approach that at scale can reduce the performance of the system. Alternatively, these behaviors are manually programmed by interleaving commands, a tedious and conceptually-restrictive process which does not fit into an iterative design practice.

In this paper, we extend the definition of a perceptual scheduler [3] to apply to distributed actuator systems. Firstly, we describe a Perceptual Task (PT) compiler , which uses the different mechanical, perceptual, and software (MPS) profiles of actuators to convert high resolution tasks into perceptually accurate, correct, and synchronous output.

We introduce the ExPRESSO Perceptual Task Scheduler (**PTS**), a scheduling mechanism which factors a perceptual model that utilized principles from psychophysics literature [10], as well as Gestalt psychology. We show how it is able to operate on a portion of system bandwidth by extending Abeni's et.al. work on Constant Bandwidth Server (CBS) [1], to incorporate a temporal dithering technique and a perceptual saliency queue. Together, the PT compiler and the **PTS** mechanism demonstrates a full pipeline for enabling distributed behaviors.

Lastly, we define an perceptual error metric that can be used to evaluate the perceptual quality of the output. Using a synthetic macrobenchmark, we demonstrate that the **PTS** mechanism is able to maintain the quality of service (QoS) of its perceptual tasks over different hardware profiles, while degrading gracefully under oversubscription.

BACKGROUND

Scheduling

The CBS algorithm [1] provides certain guarantees to systems that have a wide diversity of tasks. However, applications where output is the main actor have different constraints than just making a deadline. Lottery scheduling provides certain statistical guarantees against starvation [13], however the synchronization property of perceptual tasks requires a much harder guarantee. The most problematic issue for scheduling

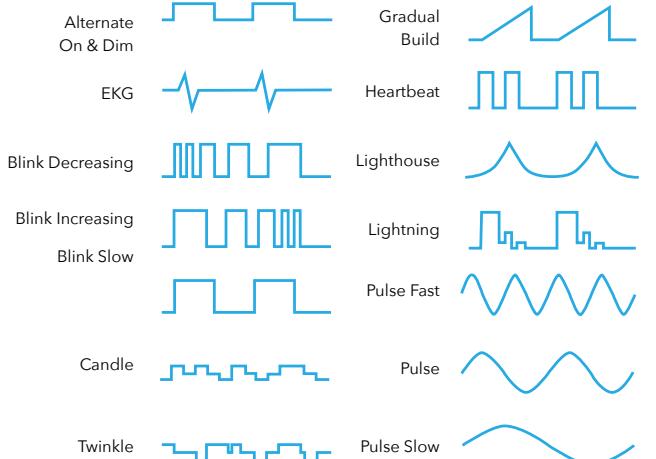


Figure 2. Example behaviors for point lights, encoded as pulse code modulations.

mechanisms for continuous media is the skip strategy, which discards tasks in order to modulate the flow of soft tasks.

Terminology and assumptions

In our system, we model an interaction as sending a signal, or task τ , mediated by an actuator A , to produce a perceptual output behavior B . We define these entities below.

Tasks. We consider a task τ to be any set of jobs that causes an actuator A to perform a series of actions. Thus a task $\tau_{A,i}$ for actuator A contains a sequence of jobs $J_{A,i,j} = \langle t, I \rangle$, where t denotes the request time and I denotes the PWM signal issued by the j^{th} job of task $\tau_{A,i}$. Tasks are the actuator-level representation of a behavior. We also assume that there exists one job per unit time for a given actuator.

Actuators. An actuator with input range I_r is modeled using three types of profiles, hereforth termed the MPS profile, encoded as lookup tables:

- *Mechanical impedance profile $M(v)$* - this represents mechanical latencies due to structures resisting motion for each v vector (e.g., certain stepper motor requires at least 100ms to go from min to max)
- *Perceptual, or Gamma, profile $G(P)$* - this represents the conversion from perceptual magnitudes to PWM signal (e.g., 50% brightness on an LED [$I_r = [0, 255]$] is equivalent to a 39 PWM load)
- *Software impedance profile $S(v)$* - this represents the software latencies at each for each v vector in PWM signal(e.g., BlinkM introduces a 20ms delay to each value change)

Aside from the perceptual profile, the values must be generated experimentally or derived from manufacturer documentation. We compiled a set of 15 actuators available through our public API. The perceptual profile can be modeled using Equation 2.

Behaviors. At the human-level, behaviors B are defined as tasks which semantically convey information and are encoded in perceptual space, as opposed to actuator-intensity

space. We encode behaviors as a 12-bit pulse-code modulation (PCM) sampled at 128Hz (Figure 2). PCM is an uncompressed encoding format regularly used for audio applications, which samples and quantizes analog values at regular intervals. These behaviors were derived from field work conducted by Harrison *et. al.* for point-lights [4], as well as from custom built program-by-demonstration interfaces. We represent a PCM signal W as a sequence of tuples $\langle t, P \rangle_i$, where t denotes the sampled time and v denotes the perceptual magnitude issued by the i^{th} sample of the signal.

Furthermore, we assume the following properties that are currently ubiquitous amongst embedded systems.

- For any actuator A , the WCET of each job has low variance since most processing is offset by hardware components (e.g., internal controller in stepper motors), and thus the WCET of these jobs is I/O bound and regular. However, while this predictability adds more flexibility to scheduling routines, it is important to note that the density of jobs for a task τ_i can *and often* changes for each period T_i as well as from actuator to actuator.
- Another important distinction of a task is that its jobs hold state. Issuing a job at $\langle t = 1s, 120 \rangle$ and $\langle t = 2s, 120 \rangle$ is redundant since the 120 PWM load persists from $t = 1s$ until another command changes its state.

Lastly, we will be referring to terms and concepts prevalent in psychology literature, however most relevant to the application of a scheduler is the *Just-Noticeable Difference* (JND) which can be conceptualized as a unit measure of perceptual time. Formally, JND is defined as the amount a stimulus must be changed in order for the difference to be detectable at least half the time. This measure is used in experimental psychology to calculate perception of stimulus e.g., lux \rightarrow brightness, amplitude \rightarrow loudness, temperature \rightarrow heat, and has been used by Chaudhary *et. al.*[3] for perceptual scheduling of audio stimuli.

Throughout this paper, our scheduler will be using the JND unit time scale, which is experimentally derived as follows:

1. Serially send n equivalent sine-wave tasks to each actuator in the system.
2. Adjust the period T_i of the sine-wave until all actuators appear *just-noticeably* synchronous to obtain

$$k = \frac{T_i}{n} \quad (1)$$

3. Repeat trial varying n , and report the median value k over all trials.

For the Arduino UNO atmega328 microcontroller, we report $k = 0.585ms$, over 10 trials and 5 participants, and a randomly sampled n -actuator range of [1-40].

Since the ratio of JND/reference has been observed to be roughly constant, psycho-physicists use the Steven's Power Law formulation to map physical stimulus I to perceptual stimulus $\psi(I)$.

$$\psi(I) = kI^a \quad (2)$$

Notably, this formulation is used to gamma-correct modern LCD displays; we use this formulation in our system but utilize it to adjust other non-light based modalities.

Perceptual Task Compiler

The major role of the PT compiler is to convert perceptual-space behaviors into an equivalent actuator-space representation τ_A , conditioned on the type of actuator A . Behaviors are encoded at a higher resolution than is needed for mechanical actuators, thus we define a set of filters that can be used to reduce the complexity of the incoming signal, as well as convert to actuator-space. We define the PT transform as F_A on the poset behavior B to yield the poset task τ .

$$F_A(B) = (F_S \circ F_M \circ G)_A(B, \leq) = \tau \quad (3)$$

The PT function F_A is comprised as the composition of three transforms, derived from the MPS profiles for actuator A .

The gamma correction transform G is as follows:

$$G_B = \{P^{1/\gamma} \cdot \frac{\max(I_r)}{\min(I_r)^{1/\gamma}} | t, I_r \in B\}$$

where γ is the Stephen's Power Law exponent from Equation 2, and I_r is the input range for actuator A .

We then apply the mechanical and software correction transform by first taking the derivative of B :

$$B' = \frac{d}{dt}(G_B) = \frac{dI}{dt} = v$$

and apply the following filters which drop impossible actuations as defined by the mechanial M and software S profiles.

$$F_M(B', \leq) = \text{isDefined}(M(v))$$

$$F_S(B', \leq) = \text{isDefined}(S(v))$$

At the conclusion of applying *each* of these filters, redundant values are removed from B such that τ is the sparse representation of the original behavior.

Admission criteria

This software (S) and mechanical (M) profiles can be used to detect behaviors B that cannot be achieved on actuator A . This is used as the admissions criteria by the compiler. Often times, the original behavior can be modified by some time scalar c . We can obtain the maximum and minimum c such that every actuation in B is admissible by taking the ratio of the minumum allowed v in M or S to the minumum v in B :

$$c_{\min} = \frac{\min(B')}{\min(M(v))} \quad c_{\max} = \frac{\max(B')}{\max(M(v))} \quad (4)$$

Additional metadata

We extend the task τ_A with two additional properties for each job in its sequence. These properties takes into account Gestalt psychology and are applied as a perceptual optimization.

- *hardness* (h) - a synchronization parameter. Directionality of elements is a main grouping mechanism (e.g., moving elements that are moving in two different directions are perceived as groups).

- *locality* (I) - areas in the fovea, or center of vision, are much more perceptually stringent than peripheral elements.

The hardness parameter is composed from B' , specifically when jobs express a change in direction of the PWM load, i.e., $v = 0$ or $v = \max(I_r)$. Let the set of directionally shifting jobs be defined as:

$$v_{\text{shift}} = \{i \mid i, v = 0 \text{ or } v = \max(I_r) \in B'\}$$

We also include the first and last job index to v_{shift} . Each job is assigned a hardness value equal to the inverse of the shortest euclidean distance to a shifting value as follows:

$$h_i = \frac{1}{\min(d(i, v_{\text{shift}}))}$$

for the i^{th} job in task τ . As such, large changes in intensity are assigned a higher hardness whereas smooth changes are assigned lower hardness.

Lastly, a locality property l is defined based on the physical topology of the actuator system. In our implementation, we defined hand-defined centers of the topology, and assumed a physically static layout. For a more dynamic approach, one can construct a graph and run a centroid-based clustering algorithm. We leave this for future work.

In conclusion, a task τ consists of a sequence of jobs $J_i = \langle t, I, h, l \rangle$ which is then fed into our perceptual scheduler.

Perceptual Task Evaluator

Using a perceptual model derived from known stimulus power-laws in perception literature, we can use psychophysics method-of-constant-stimulus with human subjects to evaluate the quality of service (QoS) of the perceptual scheduler. However, this is an expensive form of evaluation. We can synthetically evaluate perceptual accuracy as a peak-signal-to-noise calculation (PSNR) from the original PCM behavior B and the output signal τ . We can calculate the total JND units that were lost by converting back from gamma space using G' and sampling the output at the same sampling rate f (128Hz) as the originally encoded B . We define the QoS for a task τ as the sum of lost JND units over the energy of the overall task as follows:

$$G'(I, I_r) = \frac{\max(I_r)^{1/\gamma}}{\max(I_r)} \cdot (I)^{\gamma}$$

$$\text{PSNR}(B, \tau) = 10 \cdot \log_{10} \frac{\max_I}{MSE} \quad (5)$$

$$= 20 \cdot \log_{10} \int_{t_0}^{t_f} \frac{2^k - 1}{\sqrt{\|G'(B(t) - \tau(t))\|}} dt \quad (6)$$

where k is the PCM resolution and $dt = 1/f$. While we can extend this error metric to penalize more for synchronization and other perceptual errors, we use this form to calculate a lowerbound on perceptual error, as opposed to using a more complicated and less general metric.

Perceptual Scheduler

We implemented our scheduler in Python and sent the final schedule through a serial connection to our testbed systems. Actuation behaviors were previously compiled and stored in a SQL database. Although not directly ported onto the embedded system, the current pipeline can be emulated on an embedded system since the serial communication is not the I/O bound, and precompiled behaviors can be loaded from an external memory cache or retrieved from a WiFi module. The cost of running scheduling tasks will increase, but we show that using a CBS scheduler, we can modify the allowed budget that is allocated to the scheduler to allow other system tasks (such as reading sensor values) to operate.

The perceptual scheduler is constructed as a CBS scheduler, where each node in the system is modelled as a server s with tuple $\langle Q_s, T_s \rangle$, where Q_s is maximum budget, and T_s is the period of the server. All perceptual tasks τ are treated as hard tasks, since its WCET is known.

A perceptual baseline - EDF parameters

According to Lemma 1 from [1], a task τ is EDF schedulable if and only if $C_i \geq Q_S$ and $T_s = T_i$.

By assigning $U_s = 1/k$ as derived in Equation 1, we can obtain the EDF parameters (C_i, T_i) . The maximum budget C_i is equal to the number of job collisions over time, and can be derived by taking the histogram of a task τ binned on deadline t as follows:

$$C_i = \max(\text{hist}(\tau, t)) \quad (7)$$

with a period equal to $T_i = C_i/U_s$.

For a n -node server where each actuator node is sent identical tasks, at least $n \cdot k$ ms are needed to actuate the nodes perceptually synchronous, and no more than a budget of n is needed.

Schedulability test

In order to prevent speed up effects when scheduling soft tasks, a known technique for CBS schedulers is to use a skip strategy: when a job finishes after its absolute deadline, the next job is skipped. This strategy violates our guarantees for synchronization. As such, perceptual tasks must be treated as hard tasks.

THEOREM 1. *Let H be the set of identical hard task τ sent to each actuator A_i in a n -actuator system. Given that the WCET of each job in τ is k , then H is only schedulable if CBS is EDF-reducible with parameters (Q_s, T_s) where $Q_s \geq \max(\text{hist}(\tau, t))$, and $T_s \geq Q_s/U_s$.*

PROOF. A set of hard tasks are considered EDF schedulable [14] if:

$$U = \sum_{i=1}^n \frac{\text{WCET}(J_i)}{T_i} \leq 1 \quad (8)$$

for n processes. Since $\text{WCET}(J_i) = k$ and since each task τ has identical $T_i = T$, this results in an schedulability test of $n \cdot k \leq T$.

Given that $T_i = C_i/U_s$ [1] and $\text{CBS}(Q_s, T_s)$, we prove by contradiction:

$$\begin{aligned} n \cdot k &> T \\ &> C_i/U_s \\ &> \max(\{\text{hist}(\tau, t) | \tau \in H\}) \cdot k \quad (\text{Equation 7}) \\ &\not\geq n \cdot k \end{aligned}$$

Therefore, H is schedulable if CBS is EDF reducible. \square

As such, degradation of the perceptual signal occurs when these EDF constraints are not satisfied. A CBS server with these EDF parameters serves as a baseline where every job is guaranteed to be schedulable.

Perceptual saliency queue

As an optimization, we change the enqueue routine for the CBS algorithm from a FIFO, to a priority queue that can be used to model saliency within the perceptual system. Within each quanta, jobs are assigned the following priority:

$$J.\text{priority} = (1 - \frac{1}{J.l}) + 10 \cdot \frac{1}{J.h} + 1000 \cdot J.$$

where a job closer to a perceptual center (locality l) has a higher priority, tie broken by jobs that have directional changes in intensity (hardness h), and finally resolved by the earliest deadline t . By Equation 1, the top Q_s jobs are accepted, and the rest are placed into the temporal dithering routine.

Temporal dithering

In order to increase the CBS capacity and scale the number of nodes in a system, we extend the CBS algorithm to schedule jobs which failed the schedulability test, hereforth termed rejected jobs, in quanta with available budget, however we modify the job dependent on its new quanta location. We accomplish this through a technique temporal dithering as detailed in Algorithm 1.

EVALUATION

In order to evaluate our scheduling mechanism, we used the Perceptual Task Evaluation (PTE) metric (Equation 6) to simulate perceptual accuracy. We define four different schedulers to observe the full effect of each portion of the pipeline: Earliest Deadline First (**EDF**), Constant Bandwidth Server with skip (**CBS-S**), and the Perceptual Scheduler (**PS-A**) without saliency queue, and the full-featured Perceptual Scheduler (**PS-T**).

Ultimately performance of our system will be evaluated experimentally through a JND psychophysics experiment. That is, given a set of perceptual tasks on a n -node system, does a user notice a lapse or abnormality in the output? The microbenchmarks we chose will focus on finding the conditions where a user may see such a lapse or degradation of quality. Although we do not conduct a user study in this paper, the results from the PTE metric has correlated well with output from our experimental setup. We leave the human evaluation for future work.

Algorithm 1: Temporal Dithering

Data: Let J_r be a job from the task τ rejected from quanta q_r , with closest available quanta q_C at time CT . Let J_N as the nearest job in the τ sequence scheduled in quanta q_N at time NT .

for J_R in *rejected jobs* **do**

- if** $\neg J_{close}$ **then**

 - delete J_R ;
 - return;

- $d = ||N - C||$;
- $pos = C + d$;
- if** $C = N$ **then**

 - $J_N := \text{lerp}(J_R, J_N, pos, d)$;
 - delete J_R ;

- else**

 - $J_R := \text{lerp}(J_R, J_N, pos, d)$;
 - $q_i.\text{enqueue}(J_R)$;



Figure 3. A testbed system consisting of 38 actuators, each individually controlled by a 16 MHz atmega328 micro controller (Arduino Uno, $Q_s = 10$) through a 12-bit PWM I²C interface (PCA9685).

Testbed - 38-node system

A testbed system (Figure 3) was constructed using a 16 MHz atmega328 micro controller (Arduino Uno) modified with three 16-channel 12bit PWM I²C drivers (PCA9685), for a total output capacity of 48 actuators. Our prototype consisted of 32 LEDs (8R, 8Y, 16G) and 5 micro servos (TowerPro SG90). Alternative testbeds were constructed to prove the feasibility of other actuator modalities (e.g., steppers, heat-pads), although these were not added to the final system.

As depicted in Figure 1, behaviors were stored on an external server, which would then be perceptually compiled. While we have only one node in our envisioned distributed network of actuator components, we anticipate that devices will propagate instructions similar to current sensor streaming techniques. Global clock synchronization is necessary to provide a seamless experience; for this reason, we use the tunable parameters Q_S of our **PS-T** scheduler which we show below can be adjusted to fit the performance of different types of hardware, degrade gracefully, and still enforce deadlines.

Microbenchmarks

In our survey of actuator behaviors in interactive devices, we noted three characteristics of behaviors:

- Synchronicity - behaviors were either intended to synchronize with each other, or propagate through the system (e.g., follow-the-leader, burst).
- Discrete/smooth - some behaviors require discrete shifts in intensity (e.g., SOS), while others follow a smooth curve (e.g., lighthouse).

As such, we developed a (2x2) microbenchmark factorial design evaluated on a CBS scheduler and the PTS scheduler on a heterogeneous configuration — the system is composed of multiple types of actuators.

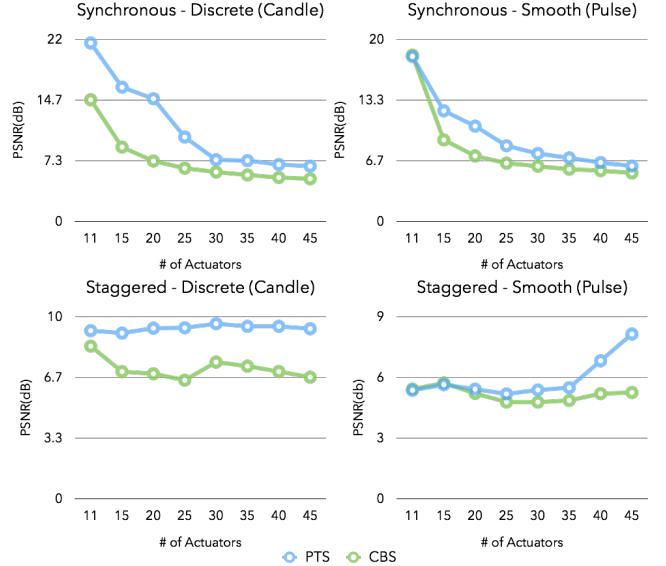


Figure 4. Microbenchmark tests altering the number of actuators in the system. These results were simulated in a budget ($Q_s = 10$) on a heterogeneous system. The top row displays synchronous commands to each actuator in the system, while the bottom displays staggered commands (on a 1ms time step). Larger PSNR values indicates better quality of service.

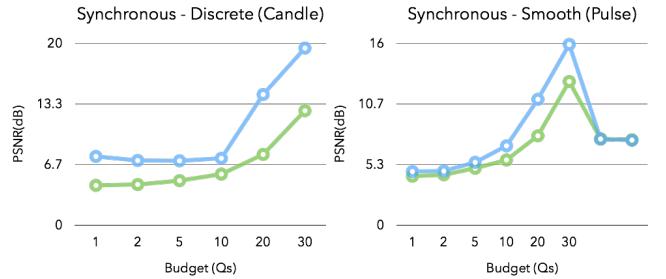


Figure 5. Microbenchmark tests altering the budget allocated to the system. These results were simulated in $n = 35$ node heterogeneous system. The top row displays synchronous commands to each actuator in the system, while the bottom displays staggered commands (on a 1ms time step). Larger PSNR values indicates better quality of service.

Results - Microbenchmarks

The result from the microbenchmarks are display varying number of actuators (Figure 4) and varying the budget allotted to each quanta (Figure 5). The graphs show a consistent improvement over the CBS scheduler.

From these experiments, we noted a potential drawback of the PSNR error metric. PSNR penalizes on overall energy, and not for shifts in energy. For example, for $n > 30$, the graphs plateau at around 7.3dB. This is due to the fact that since an actuator holds state, it can hold a constant intermediate value, cause a mean-square error to register noise.

Also, a particular abberation occurred for the staggered pulse behavior benchmark. When $n \geq 30$, the pulse behavior resonated on its Nyquist frequency, causing an increase in quality.

Macrobenchmarks

In this section, we describe synthetic macrobenchmarks developed to evaluate the system. Since actuation behaviors within distributed systems have not been fully developed, we emulate the same behaviors found in centralized multi-actuator systems.

Our example system is a theatre complex, which is composed of a projector, an eight-channel surround sound system, sixteen overhead lights, two lines of track lighting running the length of the complex, two exit signs, and a fire alarm. The behavior was composed in the context of a fire evacuation drill. The situation is marked in Figure ?? with the following events. The benchmark begins in a **IDLE** stage projector and audio system are on running at 30fps; the track lighting over overhead lights fade to begin the feature film. It then progresses to a **ALERT** stage, the alarms turns on, turning off the projector and sound, and pulsing a danger message through the track lighting. Finally, it enters an **EXIT** stage the track lights begins to propagate a signal towards the exit doors. Exit lights are then pulsing for a five minute period.

Results - Macrobenchmark

We ran our perceptual scheduler against a CBS scheduler, with a skip strategy. This resulted in an EDF behavior where periods with full utilization rejected tasks that overspent the allotted budget. The schedules were evaluated as time-signals, where logs were kept for commands sent to each actuator. These commands were reconstructed, and integrated at a supersampled rate to obtain the JND error. For the macrobenchmark report a PTS PSNR of 11.0574422702, and a CBS PSNR of 10.8947625321. We anticipate that this slight difference is due to the confounding effects of the PSNR metric and leave for future work a evaluation metric that penalizes missteps.

FUTURE WORK

Also, while our current Gestalt marking technique for high-priority jobs does aid in the perception of synchronization, certain behaviors such as ones with random elements, are corrupted by this optimization. A user could define higher-order semiotic points along the tasks that demarcate important synchronization areas.

Currently, we have behaviors developed for light and angular motion. However, more extreme actuation profiles, such as those from a heat pad, could introduce some additional variables into our PT compiler. We anticipate testing the extendability of the PT compiler under heat, tone, and vibration in the future.

Lastly, our approach currently experimentally evaluate on a single controller system. While we have only one node in our envisioned distributed network of actuator components, we anticipate that devices will propagate instructions similar to current sensor streaming techniques. Global clock synchronization is necessary to provide a seamless experience, and as such the system will likely need to account for clock skew.

LIMITATIONS

Our current evaluation metric, while taking into account the human perceptual system, is incomplete without a formal user study. In the audio perceptual scheduler, Chaudhary utilized a 5-point Likert scale evaluation to quantify the perceived loss of quality [3]. We anticipate using a similar technique to evaluate the quality of service of the scheduler.

A major limitation of our work is that we do not take into account audio actuation. Since this is a major area of study, and the most diverse of the modalities, we excluded it from our scheduling mechanism. However, incorporating a synchronized audio routine is certainly necessary to complete the scheduler for use by industrial and interactive device designers.

CONCLUSION

In this paper, we showed that physical coordinated stimuli require a different metric of performance. Factoring in perception literature, we create a perceptual compiler which converts perceptual tasks, which are highly dependent on the type of actuator used to output them, into uniform tasks which produce correct actuator instructions and perceptually equivalent output. Building off the work of the CBS algorithm, we show that the scheduler can operate on a fraction of the total allowed bandwidth. Over previous fair-allocation schedulers, we show that our PT scheduler is able to maintain a higher perceptual performance (70% - 99%) running on a conventional atmega328 microcontroller on a 38-node system. We also show through simulation that the PT scheduler allows control of up to an orders of magnitude more actuators with an acceptable loss of quality.

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