Odyssée: A new kinetic actuator for use in the home entertainment environment

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Abstract:

The paper describes a new motion generation system to be used in the context of home-entertainment presentations. Built around four high-performance, DSP-driven, brushless motors, the system is remarkably linear, and exhibits very high spectral dynamics, with a flat bandwidth from DC to 50Hz, and with significant response even above 100Hz. The paper describes the innovative technological choices which have made the system possible, including the development of a new motion profile transmission protocol ("KineLink"), which provides sampling and synchronization to the four actuators, and supports several levels of fault protection.

Each of the 4 actuators is driven by a TMS320F240 DSP, which manages everything from the power drive to the fault protections, the communications protocol and the spectral correction. In addition, this gives a self instrumented design which requires very little specialized test equipment in production.

Introduction: General description of the system and the actuators

The motion generation system is composed of 4 actuators, each capable of a ½ inch travel. Those actuators are placed under the legs of a sofa, or a row of theater seats. They are coordinated by a Motion Profile Generator, which synthesizes motion in 3 degrees of freedom (up-down, forward-backward, and left-right), according to the action in the movie.
Each actuator is composed of a very high dynamic brushless motor, controlled by a TMS320F240, which drives a low friction, proprietary transmission drive.
When the platform is idle, with the actuators at mid-travel, the motors have to support the static load of the seats and their occupants. On top of this static torque, each motor can accelerate its load to at least 1g upward. The maximum static load for each actuator is 400 lbs, which gives a total of 1600 lbs for the whole platform.
Each actuator is capable of a wide range of motion profiles, from very slow/very smooth (imperceptible) movements, to very dynamic ones (vibrations up to 50Hz).
Even though the total travel is small, which is a necessary condition of home use, the impact on the perception of the movie is impressive, because it enhances and completes the auditory and visual senses. Even very subtle movements can add tremendous effects to movies, and not only in action-packed sequences.

Compared to hydraulic systems used in flight simulators and park rides, the installation is simple and straightforward. The complete system is maintenance-free.

The system supports 2 modes of operation:

- The “Encoded Mode” works on the principle that the motion profiles for a movie have been edited in studio. Profiles are delivered on a CD-ROM which is read by the Motion Profile Generator. The profiles are synchronized to the movie from information sampled from the SPDIF audio bit stream.
- The “Audio Mode” works when the motion profiles for a movie do not exist. In this case, the profiles are synthesized in real time from the available audio channels. Even though this mode is less refined than the preferred “Encoded Mode”, it still works in a very solid manner, in particular thanks to the availability of signals from the effects channel (sub-woofer) in DVD systems, which is a very good indicator that some form of action is taking place in the movie.

The rest of the paper focuses on the technological choices which contribute to the performance of the actuators.

Motor/Drive concepts

The Motor and drive concepts are very simple, and are designed for low cost, small size and high performance. Most of the functions and sub-systems of this actuator are actually implemented in software, including most of the protections. This approach yields an extremely flexible design, where hardware (hence cost) is kept at a minimum.

As illustrated in figure 1, a 3 phase bridge of IGBTs is directly powered from a rectified 120/220V-50/60Hz.
This bridge is driven in Vector Space PWM by the TMS320F240, at high frequency (15KHz), so that the switching noise is inaudible.
The drive is not isolated, the whole control system is referenced to the lower rail voltage, which is at a live potential from the AC ground.
To keep cost and size down, the motor current is not measured. Instead, it is estimated from a real-time model of the motor, using the measured position and speed of the motor, the PWM ratio, the winding resistance and a measurement of the rail voltage. This solution requires no sensors, except for the position sensor for the motor (shaft encoder), which is also necessary for the position servo loop, and a temperature sensor in the motor, which is also necessary for the over-temperature protection.
The winding resistance is estimated from a measurement of the motor temperature.

The ripple of the rectified and filtered AC rail is forward compensated from a real time measurement of its voltage, which gives a surprisingly ripple-free motor torque. This solution had been presented at DSPS Fest 1998.
The position of the motor is measured by an optical shaft sensor which gives 3 commutation track signals, as well as an incremental encoder with a resolution of 4000 points/revolution.
At startup, when the position of the motor is still unknown, the commutation tracks are used to give a rough estimate of the rotor position. This estimate is used until the first transition is captured on the commutation tracks. At this point, the rotor position is known to a much greater precision, and the transition is used to set an absolute reference for the incremental encoder. The encoder alone is used from this point forward.
To avoid audible artifacts which might arise from "beating" between several processes, all these processes, as well as the servo control itself are performed synchronously, at the PWM frequency.
All of these choices, although costly in computational power, yield a very smooth and linear drive, exhibiting no detectable noise or vibration.

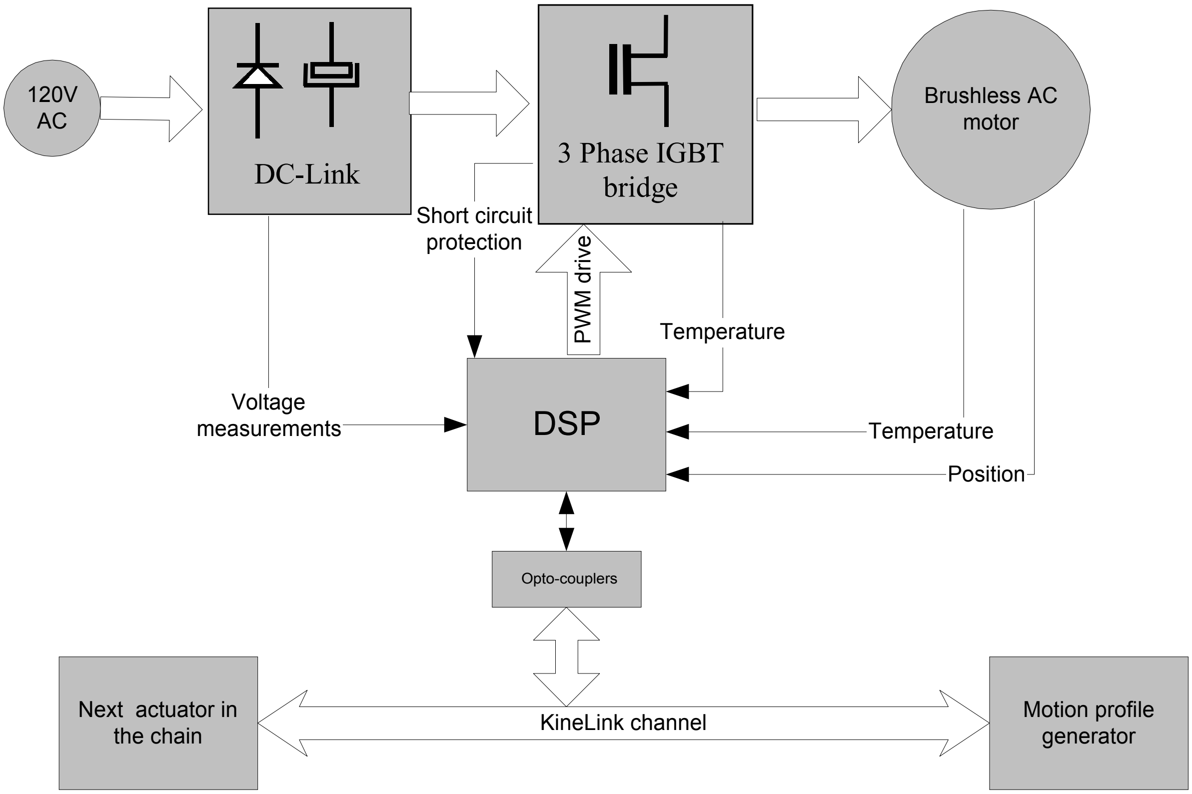

Figure 1: Actuator architecture

On the hardware side, the design is "minimalist", featuring only the DSP, IGBT drivers, and IGBTs, as well as a few operational amplifiers and comparators for the conditioning of analog signals.

Control loop

The control loop is a simple Proportional Integral Derivative (PID) servo loop on the position signal. This loop operates directly at the PWM frequency (15KHz).
Upstream of the servo loop, an interpolation (anti-aliasing) filter is used to convert from the set-point sampling frequency (KineLink - 400Hz) to the PWM and control loop processing frequency (15KHz). This filter is important to filter out any audible artifacts from the aliasing of the input sampling rate.
A correction filter is used at the front end, to obtain a flat frequency response up to 50Hz in small signals. In the present implementation, the frequency is corrected up to 40-50Hz. This filter is optimized to correct the natural frequency response of the closed-loop system. Figure 3 shows the frequency response of the uncorrected system (gray), of the correction filter (red), and of the simulated corrected system (blue). Figure 4 shows the real frequency response of the actuator, with the integral correction active.

The correction filter is important to give a good control of the play back across the useful bandwidth of the actuator. This is especially important at high frequency (above 10Hz) for the play back of vibration profiles. The correction is only accurate for small signals (1/10th the total travel), because it obviously does not alleviate the power and speed limitations of the motor. However, the response at high frequency (for vibrations) does not usually require large excursions.
As can be seen from the graph in figure 3, the effective corrected bandwidth borders on the audio spectrum.

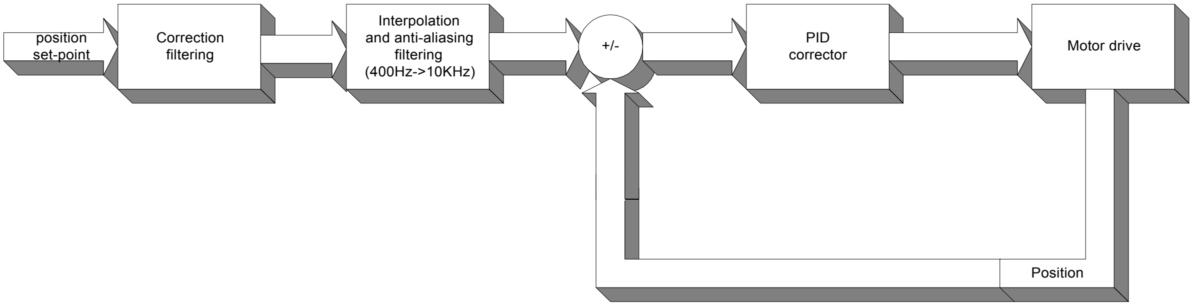

Figure 2: Control loop

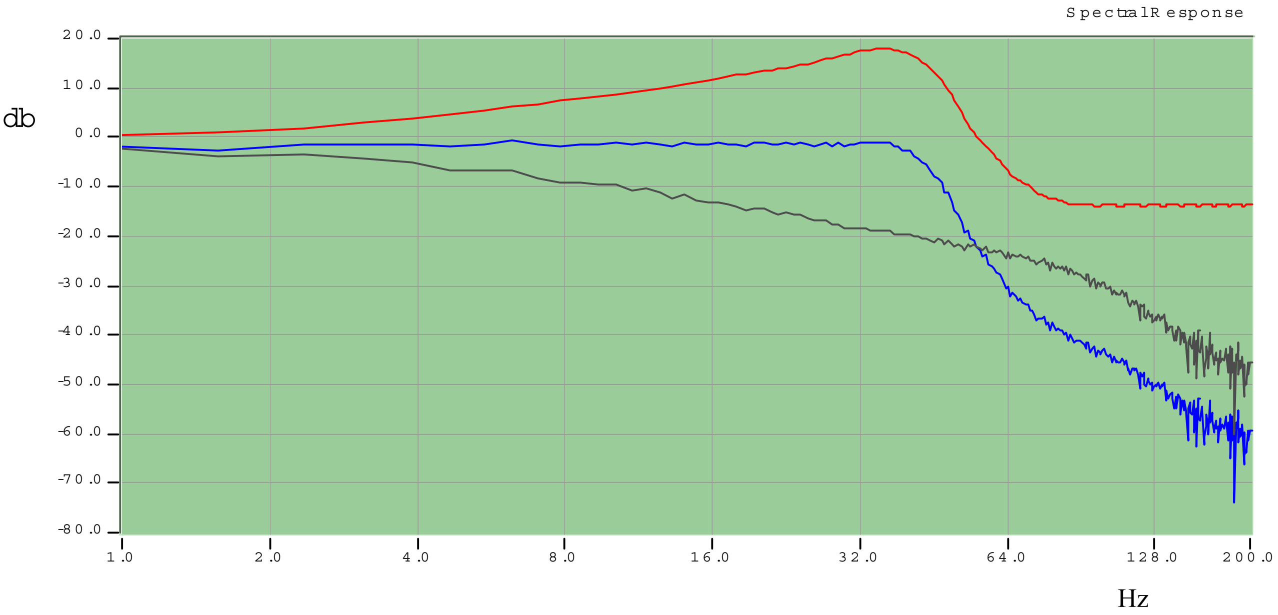

Figure 3: Small signal response correction

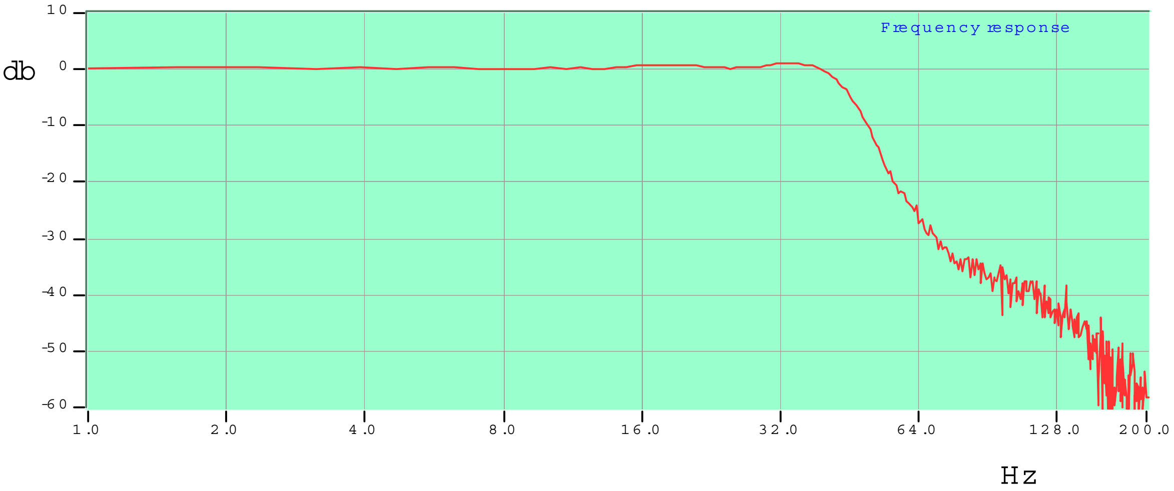

Figure 4: Real small signal response of the actuator after correction

Instrumentation and Fault protection

Given the high-power nature of the system, and the fact that it will most often be operated by non-technical users, a large emphasis has been put on the fault protection sub-system. This sub-system must be reliable, robust, and most importantly, as transparent as possible to the user.
All faults are processed at the level of the actuator, although some amount of high level fault management is done by the Motion Profile Generator, through the communication link. Most faults are processed by the DSP software which gives the advantage of reacting to fault conditions in an “intelligent” manner (for instance a temperature fault will not trigger an instantaneous shut down the drive, but will lead to a controlled park instead).

The fault protection sub-system is fed information from a group of sensors and estimators:

- Temperatures of motor and IGBT bridge are measured by thermistors placed inside the bridge and motor.
- Position is measured using a incremental encoder, and commutation tracks placed on the shaft of the motor.
- Supply voltages are measured for the high-voltage rail (power section), and the low voltage supply (upstream of the logic section regulators).
- Bridge current is measured by shunts in the upper and lower power rail.
- Motor current is estimated from a real time model of the motor.

Several classes of faults are defined, according to their mechanism (hardware or software), and according to their latency.

- **Hardware fault**: The only hardware fault is the bridge protection fault. This fault is triggered by an over-current in either of the rail shunts. It shuts down all PWM outputs in less than 3µs, which is fast enough to protect the IGBTs in case of a short. If properly driven, the IGBTs are able to sustain a short for 10µs.
- **Fast acting software faults**: Two software faults necessitate a fast reaction:
  - **Logic Supply Under-voltage**: In case of an under-voltage of the power supply of the logic section (DSP, IGBT drivers, etc…) it is critical to stop driving the IGBTs, to avoid a situation where the IGBTs are driven with gate voltages too low to saturate them completely, which would bring them into high dissipation operation, and ultimately into failure. This situation arises when power is cut in a non controlled manner (with the drive still active and high currents in the bridge). These protections act in 500µs, fast enough to avoid the critical situation. They are always enabled. In particular they also act during the power-up to inhibit the drive until the logic supplies are properly established.
  - **Encoder/Commutation tracks failure**: Whenever the position read by the incremental encoder does not agree with the information from the commutation tracks, the position of the rotor

is not safely known. The real time model of the motor, and the estimated current inferred from this model are no longer valid. The drive is stopped immediately, to avoid driving the motor erratically, possibly with large over-currents. This situation could arise if noise is present on one or the other of these sensors, or if either fails. This is a high priority protection, with a latency of 70µs.

- **Fast acting temporary fault**: One software fault is temporary and fast acting:
    - **Over-voltage**: As can be seen from figure 1, the drive does not have a breaking capability. Normally, since the travel is small, the energy fed back to the DC-Link capacitors is within reasonable limits. However, in some cases, for full travel downward ramps, with a static weight close to the maximum, the DC-Link voltage can grow so high as to put the DC-Link capacitors in danger of over-voltage. In this case, the ramp is halted immediately, and stays halted as long as the voltage remains too high on the capacitors. This behavior may happen more often after a large number of operating hours, when the DC-Link capacitors have aged and lost some capacity. This is an example where intelligence in the drive contributes to keep the hardware costs and size down (no breaking circuitry, smaller DC-Link capacitors) with virtually no impact on performance (in this case the cost is a small glitch in the motion profile, very rarely, when the load and downward travel are both high.
- **Controlled reaction software faults**: The other software faults can tolerate a longer latency, and lead to a controlled "park" of the actuator that lasts a few seconds. These faults include:
    - **Over-weight**: The time averaged estimated current acts as an indicator of the static weigh that the actuator is seeing. This fault is triggered when the 400 lbs limit is exceeded.
    - **Over-temperature**: In case of an over-temperature of either the motor or the drive, the actuator is also parked in a controlled manner.
    - **Travel**: The full travel is tested at startup by looking for the upper and lower stops. In case the distance between the stops is not within a specified tolerance, the drive is parked and the system will not start. This fault is usually indicative of a mechanical problem, limiting or blocking the movement.

KineLink

The 4 actuators are connected to the Motion Profile Generator which controls them, through a dedicated communication link called KineLink.
KineLink is a specialized protocol which serves 4 purposes:

- Transports motion profiles from the Motion Profile Generator to the actuators, These motion profiles are sent as four continuous streams of position samples.
- Transports possible fault information from the actuators back to the Motion Profile Generator. The Motion Profile Generator displays this information to the user. Eventually if one actuator experiences trouble and goes into "park", the Motion Profile Generator also parks the 3 remaining actuators to avoid a situation where the platform is held by only 3 actuators.
- Transports information about the operation of the actuators back to the Motion Profile Generator. This is used for testing purposes.
- Insures the timing and regularity of the input sampling rate, which is important to avoid audible and vibration artifacts from a sampling frequency exhibiting jitter and variability.

KineLink is a Multi-drop communication channel, with a Master/Slave configuration (the Motion Profile Generator is the Master and the 4 daisy-chained actuators are the slaves). This configuration is very bandwidth efficient, and saves hardware and software complexity.
The protocol uses NRZ signaling, and is opto-coupled at the level of the actuators, since the whole actuator control system is referenced to a potential which is live from the AC ground.
Its high bandwidth (57600 Bauds) allows a sampling rate of 400 samples/s (16-bit samples) for each actuator. This yields a theoretical motion bandwidth of 200Hz, high enough for most effects!
The KineLink protocol allows communications fault management, including hot connect/disconnect, and synchronization recovery. During communication fault and recovery, the 4 actuators are simply held into place to avoid erratic movements.

Development and production testing

One of the advantages of this self-instrumented architecture is that it allows easy testing during development and production. After the code has been downloaded into the DSP, it is a simple matter to connect the actuator to a PC, through its KineLink connector, and use a test application to check all hardware sections, as well as the dynamic and electronic behavior of the actuator. Such test applications rely on test functions which have been designed-in the embedded DSP code. These functions return, on demand, variables like the temperatures of motor and drive, position and speed of the motor, estimated current and weight, rail voltages (power and logic)… etc. These variables are read synchronously, at the input sampling rate, all the while sending motion profiles to the actuator. These functions also allow the on-line fine tuning of the actuator's parameters, like the PID corrector, the correction filter, the alignment of the shaft sensors… etc.

For instance, one of such test application which we developed in LabView, allows us to excite the actuator with a uniform white random signal, and extract its position response, synchronously to the excitation. With input and output vectors in PC memory, we use a Recursive Least Squares procedure to estimate the impulse and frequency response of the actuator, from which we calculate the correction. The correction is then placed in Flash ROM within the DSP.

Another LabView application allows us to excite the actuator with steps and ramps of varying frequencies, and amplitudes, and for different loads, and to examine the increase of the power rail voltage during the descent, due to breaking regeneration.

A third application yet allows us to examine the evolution of temperature with time, as a function of static load or motion profile usage.

All of these test functions do not require any specialized test equipment, other than a PC running the test application.