DISTRIBUTED ALLOCATION USING ANALOG MARKET WIRE COMPUTATION AND COMMUNICATION.

Warren B Jackson, Carlos Mochon, Koenraad Van Schuylenbergh,
David K Biegelsen, Markus Fromherz, Tad Hogg, and Andrew A Berlin

Xerox PARC, 3333 Coyote Hill Rd. Palo Alto, CA 94304, wjackson@parc.xerox.com

This paper describes the implementation of a market-based scheme for allocating and coordinating the actions of many mechatronic systems using analog electronics. The system is versatile, low cost and robust against changes in the number and capabilities of the participating agents. As an example, the analog electronic market for an airjet paper system applying forces and torques for controlled object motion has been designed, built and tested. The results demonstrate that the market approach delivers a fast response, asynchronous communication, and robust coordination of a number of agents.

1. INTRODUCTION

As the cost per unit functionality for sensors, actuators, and computers continue to decrease, mechatronic control systems comprised of large numbers of interconnected such elements become increasingly feasible. Control of these mechatronic systems with tens to thousands of components will require new developments in control design and hardware architecture. Existing methods scale poorly with the number of elements and most importantly, real time communication between large numbers of control elements is still very expensive, slow, and complex. In this work, we present a simple, inexpensive asynchronous analog electronic method for both real-time communication and allocation of actuation among large numbers of elements based on a market-like approach. This approach is distributed, flexible, easily extensible, robust to various failure modes, and reduces the communication load.

2. MARKET ALLOCATION

As in previous work (Clearwater, 1996), the market-based solution to the problem of allocating a task (or tasks) among a large number of mechatronic agents (actuators, controllers, sensors etc.) is solved when each agent bids for part of the total task as determined elsewhere in the system (e.g. by higher level controllers or external inputs). The behavior of each agent depends on its own local information as well as market prices that communicate the global information. These agents interact through a small number of markets in order to coordinate their global behavior. The market-based allocation and communication, like a real market, is robust against failure of individual agents and changes in tasks while requiring minimal communication. Only one piece of global information, namely the price, is necessary to coordinate the actions of an arbitrary and even varying number of agents in a given market.

While such market-based allocation schemes are used in control of complex systems such as the world economy or resource allocation, they are less common in electronic and mechatronic systems. Market-based control has been applied to the control of building temperatures (Clearwater, 1996; Huberman and Clearwater, 1995), unstable structures (Guenther *et al.*, 1997), computational resource allocation (Kurose and Simha, 1989), and many other distributed systems. While market based control has been shown to be robust and successful in coordinating dispersed agents, one of the chief drawbacks, heretofore, is that the speed of the market computation is relatively slow, thereby limiting its application.

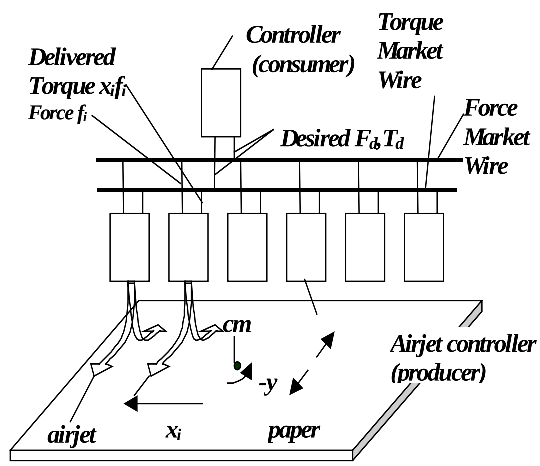

Fig. 1 Overall structure of analog market applied to 2-d object motion using airjets. The airjet imparts either –f,0,+f force in the y direction at a distance x_i from the center of mass (cm).The market system consists of one producer, six consumers, and two markets. The voltage on each wire represents the price and the current the quantity of each market commodity traded.

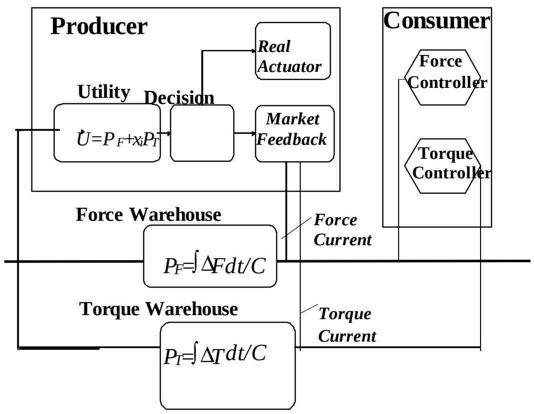

Figure 2 Block diagram of one producer (actuator) and a consumer were connected to the force and torque market wires.

3. ANALOG MARKET IMPLEMENTATION

In order to address the speed limitations of market allocation as well as to provide robust asynchronous distributed communication of the results, an analog electronic version of market-based actuation allocation was designed, simulated, built, and tested. The analog implementation greatly speeds up computation and communication of market-based task allocation in a multi-agent system. As a concrete example, the analog market allocation is applied to a specific distributed mechatronic application: the problem of controlling the linear motion in 1-d and angle of a sheet of paper using an air jet table. This mechatronic system consists of many valved airjets that move the paper by viscous drag between the air and the paper (Cheung *et al.* 1998). In this system the analog market solves the problem of deciding which binary valves should be open or closed in order to deliver the appropriate desired aggregate force, $F_d=\Sigma f_i + \Delta F$, and torque, $T_d=\Sigma x_i f_i + \Delta T$ where $f_i = \{-f, 0\ f\}$ is the y directed force

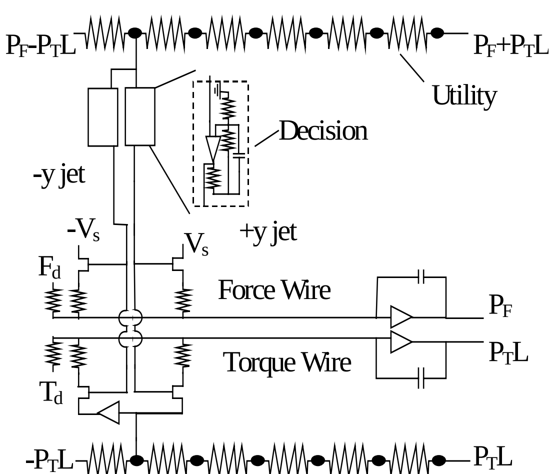

Fig. 3 Specific analog implementation of the block diagram of Fig. 1 showing a consumer block, one producer block and the market block. The combination of the market voltages through summation is not shown.

for each up-down jet pair on the paper, x_i is the position of the jet pair with respect to the center of mass, f is the magnitude of the force applied by each airjet, and ΔF (ΔT) are the total force (torque) errors (Fig. 1). The jets have a delay in actuation of about 3 msecs but can open or close anytime afterwards.

The primary components for the analog market wire solution for this application are a controller--representing a 'consumer', two wires--representing the force and torque 'markets', and one agent per actuator--representing the 'producers' (Fig. 1). The controller (consumer) adds a current to the 'force' wire in proportion to the desired force, F_d, and a current to the 'torque' wire proportional to the required torque, T_d. The producer (actuator) measures the voltage (price) on the force (P_F) and torque wires (T_F), and computes the utility function, $U=P_F+x_iP_T$ based on its position, x_i , with respect to the center of mass of the object, and a gain factor for each. The actuator (in this case an up-down valve pair) delivers a force $f_i=\{-f, 0, f\}$ depending on the value of the utility function. If U falls below the negative threshold, a force $-f$ is applied by firing the negative jet, while if U exceeds a positive threshold, a force f is applied by firing the positive directed jet. Between these values, both jets are activated yielding zero force. The corresponding currents, f_i and x_if_i, are removed from the force and torque wires, respectively. A change in the valve controller state cannot be made until a 3msec delay to approximate the delay in the application of the physical force to the paper. The utility function weights force and torque prices (voltages) depending on the position of the actuator with respect to the center of mass of the sheet of paper (Fig. 2). Thus, actuators near the edge of the paper weight torque more than force compared with the jets near the center.

The price (voltage) is proportional to the integral of the net force and torque error currents $P_F = \int \Delta F\, dt/C$ and $P_T = \int \Delta T\, dt/C$ where C is the capacitance of the market wire. This capacitance can be intentionally altered to smooth mismatches between demand and supply current just as a warehouse accomplishes such results in economic markets. The voltage on each 'market' wire represents the 'price' of the commodity and fluctuates until producer and consumer currents are balanced. At equilibrium, if each agent produces an average actuation proportional to the average current added to the market wire, the combined actuation task is accomplished. As the number or capabilities of the producers change over time, each of their portion of the force and torque actuation tasks are reallocated to insure that the currents balance. This market wire approach appears to be a promising architecture for both computation of allocation among large numbers of elements and asynchronous communication of the results along the wires.

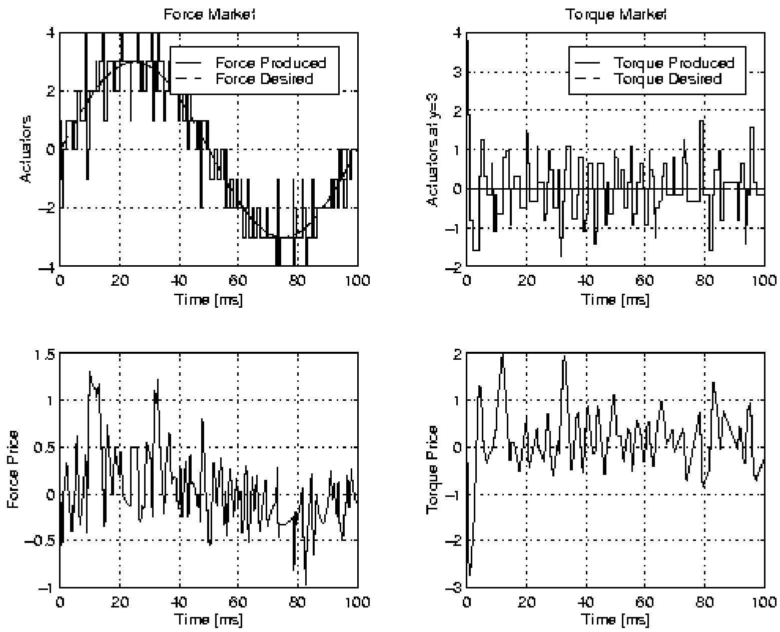

Fig. 4 Oscilloscope traces depicting the market circuit delivering desired force and torque vs time (top left and right, respectively) and the corresponding force and torque market price (bottom left and right)

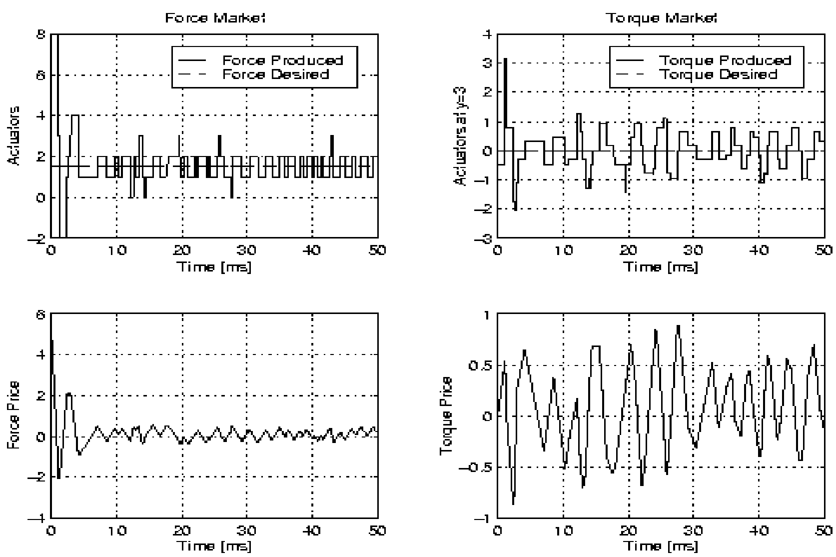

Fig. 5 Oscilloscope traces depicting the response to a pulse in the desired force for both force and torque vs time (top left and right, respectively) and the corresponding force and torque market price (bottom left and right).

4. IMPLEMENTATION

The actual implementation of the analog market is shown in Fig. 3. The utility function is computed using a resistance network with a voltage of P_F-P_TL at one end and P_F+P_TL at the other where L is ½ the size of the paper. The voltage at the intermediate nodes linearly interpolates between the two voltages. Voltages P_F and P_TL are obtained from the force and torque markets with the difference and sum obtained using a low cost analog multiplier/adder chip(AD633) (not shown). If the voltage of the resistive divider exceeds a threshold of the comparator, the voltage goes high and is used to turn on the transistors (or analog switches) to inject current into the force and torque market wires. The capacitor provides a hysteretic threshold so that the jet does not fire within 3ms of a previous state transition. The comparator is also used to trigger the airjet (not shown). Because the torque current injected on the market must be proportional to the distance from the center, a second resistive network is used to compute the distance and hence the current injected into the torque market. For a –y directed jet, the sign of the currents for force and torque must be opposite those produced by a +y directed jet. The consumer (the controller inputs to the market) provides the desired force and torque currents using the voltages F_d and T_d, respectively, across appropriate resistors. The total currents are summed and low-pass filtered using the two market op amps serving as warehouses. These pricing voltages are provided to the rest of the circuit to compute the utility function. In total, the analog market implementation requires about two op amps, two analog switches, and a few resistors per actuator to implement. Thus, implementation for many actuators should be inexpensive.

5. RESULTS

Test results demonstrate the simplicity, robustness, and capability of the low-cost market-wire approach for solving many-element mechatronic allocation problems. In Fig. 4, the market delivers the required time averaged force, a sine wave (upper left), while maintaining a constant time averaged torque of zero (upper right). The price for force and torque are shown in the lower two panels in Fig. 4. The prices are the integrals of the force and torque errors shown in the upper panels. The actuation oscillates in order to insure that the time-averaged force and torque match the desired force and torque. The minimum price fluctuation given by the smallest impulse--a jet force times 3 msec. Thus, each small excursion in the price represents the minimal impulse of a single jet. If the jets were capable of a continuous range of forces, the decision on the utility function would be a proportional response rather than a threshold, and the oscillations of the prices on the force and torque markets would be much smaller. Thus, the apparent instability of the market is not a consequence of market instabilities but rather the discrete nature of the actuators. The market is therefore providing a multi-dimensional pulse width modulated solution for a discrete allocation problem; the market wires are communicating these solutions to all the participants.

The system is stable as shown in Fig. 5 in its response to a spike in the requested force. The produced force settles back to the desired dc force and torque in less than 5 ms (upper panels, Fig. 5) while the prices of force and torque quickly return to the steady state average (lower panels, Fig. 5). The allocation of six jets is computed and communicated within a few msecs.

The system is also robust to actuator failure. In Fig. 6, a third of the actuators are abruptly removed from or added to the market by means of a control voltage (lower right panel, Fig. 6) that isolates the actuators from the market. The upper right panel verifies that actuator 3 ceases to fire when the control voltage is high. During these time periods (10-20 and 30-40 msecs), the market circuit compensates for the inactivated actuators within milliseconds keeping the price constant and the average force and torque constant (upper and lower left panels Fig. 6). Thus, the market system rapidly reallocates actuation and transmits the information asynchronously along the market wires between the actuators.

This system should scale very well to the control of hundreds of elements and accomplish allocation in time scales on the order of the op-amp slew rates (tens of microseconds or less). Importantly, no synchronization or central controller is required to communicate the global price information, and all agents can communicate simultaneously. Conflicting goals are reconciled by the implementation of an analog system. Therefore, the cost per node, an important factor in multi-component mechatronic systems, is the cost of a few circuits per node. The analog market wire approach investigated here has general applicability to many different multi-component systems and therefore has the potential to provide practical, low-cost, and simple solutions to some important problems in control and communication for large scale mechatronic systems.

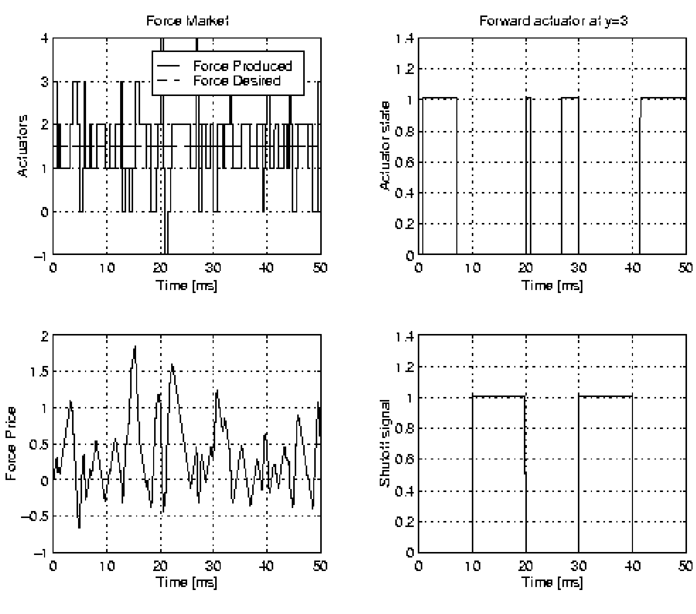

Figure 6 Oscilloscope traces showing the force produced (top right) and the force price (bottom, left) as a third of the actuators are removed from the market when shutoff signal is 1 (lower, right) and added when shutoff is 0. Note that there is no significant spike at the transition times of 10, 20, 30 and 40 msec, demonstrating robustness to changes in market participation. The upper right panel shows that one of the actuator is indeed removed (not firing) when the shutoff signal is high

6. DISCUSSION

The results shown in the previous section demonstrate that the analog market system quickly solves the problem of allocation for the airjet problem in a simple, low cost way even though the actuation task is discrete in this particular example. If the approach is to have widespread use, it is important to discuss its application and limitations to more general mechatronic allocation problems.

One possible concern about this method is scaling to large numbers of component systems. Basically, the number of possible agents that can be coordinated by the market system is given by the ratio of the maximum signal to the noise. When each agent is active, its effects on the market must be distinguishable from noise on the system. Thus, the effect of each agent must be represented by a signal that is greater than a noise signal. For the present system, the noise floor is about 0.5 mV for a 0.5 MHz bandwidth system using low cost amplifiers and a breadboard without shielding. With additional effort the noise level could be easily reduced. The maximum signal allowed is about 10V. Thus, allowing for spikes and over range prevention, the maximum signal could be about 2-4 V. Hence the number of agents that could participate in the market from signal-to-noise considerations is about 1000-8000. However, input offset currents, nonlinearities, temperature drifts, pickup and loading introduce significant reductions in these numbers. In particular, the op-amp output currents are typically limited to ten's of mA or less. The combined current of 100 agents would require that each deliver on the order of 0.1 mA. These currents could be generated using resistors in the range of 10-100kOhms for typical 10V supply. One thousand agents, however, would reduce the current to 10 μA per agent, a number that is more problematical. The combined input offset currents of 1000 op amps is on the order of $3nA\times1000=3\mu A$, a value nearly equal to the current per agent. Thus, a more realistic estimate would be in the range of 100 agents that could be accommodated using this market system. Of course, one could use multiple markets if a single market becomes overloaded.

One of the most useful aspects of the analog market based system is that the communication of the market prices is performed virtually instantaneous by the market wire. Because the communication is asynchronous, a clock pulse or clock synchronization is not necessary for the communication to occur. A competing system would involve communication over a bus such as an Ethernet or CanBus. However, neither would easily be able to handle the communications of 100 words within 1 msec for each market. Although the bandwidth of an Ethernet is sufficient, the collisions and packet overheads reduce the usable communication bandwidth. Moreover, the cost per node on an Ethernet is still on the order of $10 for the Ethernet chip and driving electronics, a value that is still quite expensive. The current implementation requires only a few op-amps, resistors, and switches per node. These components could easily be combined into a single market chip that would perform the market calculations and communications for the price of a single surface mounted chip.

Perhaps one of the biggest potential objections to the analog implementation of the market allocation is the difficulty in implementing more complex functionality such as conditional branching, nonlinear utility functions etc. that may be required for most general applications. Such more complex functions can readily be implemented using an embedded processor with built-in A/D channels to read the market price and built-in D/A channels with a transimpedance amplifier to convert the D/A output to a current to put onto the wire. Such a system could easily read the market price, compute a complex utility, and output the current onto the market wire within 1 msec or so. The cost per node of such systems could easily be less than $1 making this system flexible, universal, and low cost.

7. REFERENCES

Cheung, P., A. Berlin, D. Biegelsen, W. Jackson, R. Lau, (1998). Experimental characterization of printed circuit board-based cantilever air valves. Proceedings of the Symposium on Micro-Mechanical Systems, ASME International Mechanical Engineering Congress and Exhibition, Anaheim, CA, DSC Vol. 66, pp 285-291.

Clearwater S.H., (1996) Market Based Control. World Scientific Publications, Singpore.

Guenther, O., Tad Hogg and Bernardo A. Huberman.(1997) Controls for unstable structures. Proc. of the SPIE conference on Mathematics and Control in Smart Structures.

Huberman, B. A. and S. Clearwater (1995) A Multi-Agent System for Controlling Building Environments. Proc. of the International Conference on Multiagent Systems (ICMAS-95), pp. 171-176.

Kurose, J. and R. Simha.(1989) A Microeconomic Approach to Optimal Resource Allocation in Distributed Computer Systems. IEEE Transactions on Computers 38(5)pp. 705-717