The interactive balloon: Sensing, actuation, and behavior in a common object

by J. A. Paradiso

In the not too distant future, new materials for sensing and actuation, together with high-density, low-power electronics and embedded computation, will bring interaction and intelligence to commonplace inanimate objects in our environment. As a simple but illustrative example, we have built balloons that can interact conversationally. This paper describes this system: the piezoelectric foil that works as an acoustic pickup and speaker on the balloon, its audio characteristics, the driving electronics, the signal processing, and some applications of this technology at the MIT Media Laboratory.

I pity inanimate objects
Because they can't move . . .

—Creme and Godley, 1979[1]

The introduction of sensing, actuation, and behavior into the fabricated artifacts that surround our lives is well under way. Starting centuries ago with simple mechanical systems, we began to animate the objects in our environment. After the introduction of electricity facilitated the development of electrical sensors, signal conditioning, logic, and actuators, the devices around us evolved a more complex mapping between action and response, becoming vastly more capable and indispensable. Microelectronics are steadily growing less expensive, smaller, and more power-efficient, enabling us to realize our desires for enhanced function on the familiar objects that we encounter daily and routinely carry about. The replacement of hard-wired designs with embedded processors enormously increased their input-output complexity, allowing more sophisticated user interaction, but also bringing the attendant problems of the many cryptic buttons and displays that vie for attention in the world of digitally animated artifacts.

This trend will not merely continue; it will explode in the very near future as technology crosses the boundary where it becomes feasible to imbue most of the common (and even disposable) objects in our environment with some degree of sensing, communication, actuation, and processing. Present-day user interface logjams should evaporate as distributed sensors and processors capture our gestures and collaborate to evaluate our intent, while appropriately embedded actuators and displays give us feedback from the real and virtual worlds. The social implications of such a thoroughly animated environment are difficult to envision. Although one can readily quote specific, often amusing, scenarios in isolation (i.e., the nearly empty mug that alerts the coffeemaker for more brew when it senses your hand approaching), life in a world saturated with such capability will be vastly different from the transitional phase that we are entering now.

Peering into such a realm, the MIT Media Lab has recently launched a consortium called "Things That Think" (TTT),[2] pairing manufacturing, computing, communications, and application companies with Media Lab researchers in an attempt to address the technologies and issues implicit in moving computing, communication, sensing, and actuation into

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everyday objects. Several papers in this issue of the *IBM Systems Journal* explore various aspects of this endeavor. In this paper, a device is described that was developed as a metaphor for TTT and demonstrated at the Media Lab's tenth anniversary celebration, where the consortium was officially launched. It is a common MYLAR** party balloon, as found at any other birthday celebration. This balloon, however, is able to converse.

PVDF foil

The key to endowing the balloon with hearing and speech is a sheet of piezoelectric polyvinylidene fluoride (PVDF) film, which is a semicrystalline homopolymer;[3] i.e., a polymer in a mixture of crystalline and amorphous states. One of the crystal states is ferroelectric and thus responsible for PVDF's piezoelectric properties.[4] It is produced when a sheet of PVDF is pulled or mechanically worked. In manufacturing piezoelectric PVDF foil, this state is created by drawing or rolling the foil, after which a high electrostatic potential is applied across the foil at elevated temperature to permanently polarize the PVDF (aligning dipoles with the imposed electric field, normal to the surface). The foil is then cooled, and a conductive coating is typically applied to both foil surfaces to provide electrodes.

If such a foil is stretched, the dipoles and their attached crystalline structure move, inducing an alteration in the polarization charge presented at the foil surfaces that appears as a voltage across the metallized electrodes, which form a parallel plate capacitor with the sandwiched PVDF as a dielectric. On the other hand, an external voltage applied across these electrodes moves the dipoles and their attached structures, thereby applying force to the foil and changing its dimension. In this fashion, PVDF can be made to work as an acoustic pickup (impinging sound pressure waves change the foil shape, producing a corresponding voltage) or emitter (applied voltage changes the foil shape, producing sound).

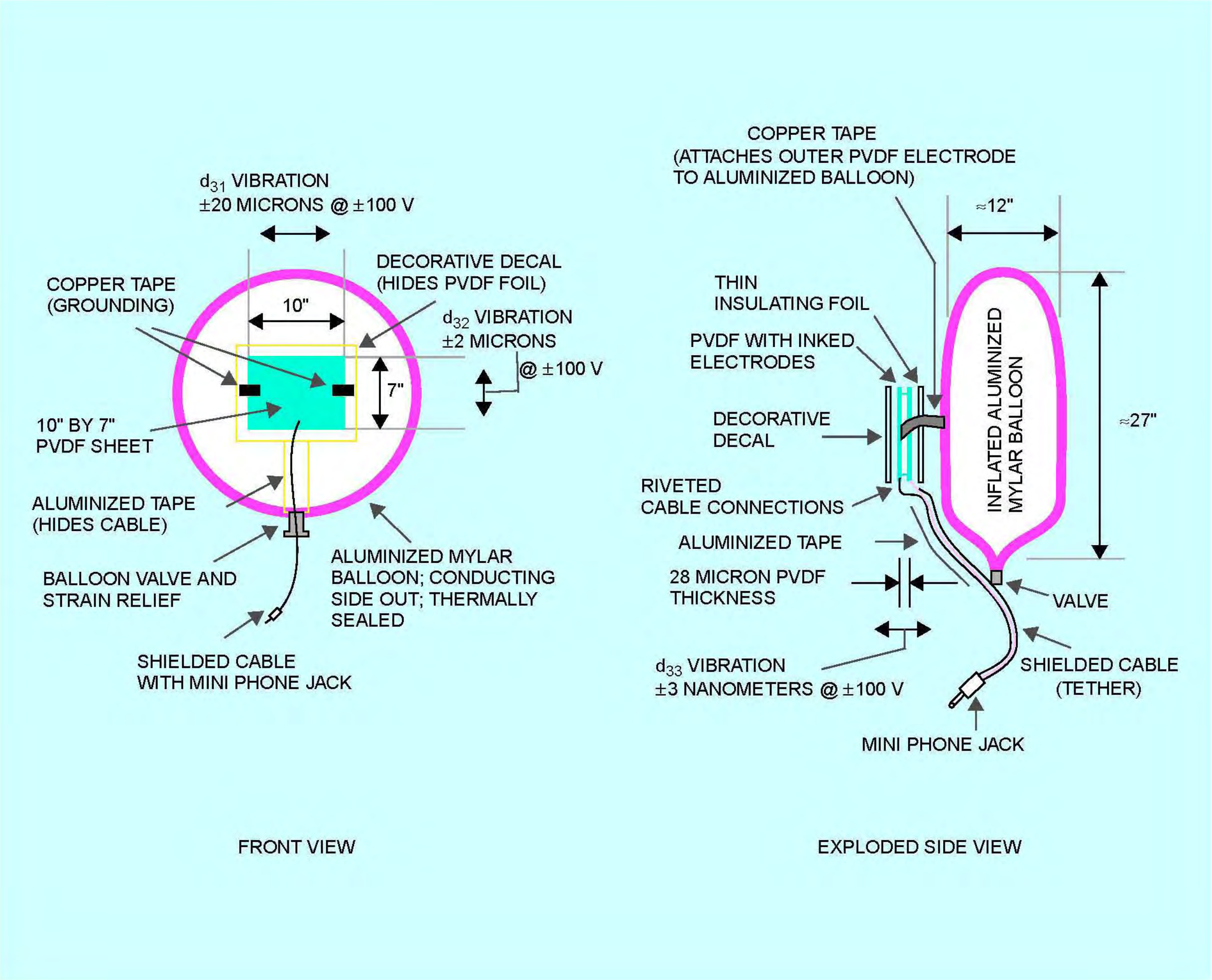
PVDF is usually fabricated as a metallized foil, with common thicknesses ranging from 9 to 110 microns.[5] Although the foil is mechanically tough, it remains quite elastic (having a Young's modulus under 2.5 gigapascals), thus it exhibits a low acoustic impedance and has a flat, broadband frequency response that can range from millihertz through gigahertz (most other piezoelectric materials are either crystals or ceramics that form highly tuned structures). It is very linear, sensitive across an extreme dynamic range of excitation (10^{-8} to 10^{6} pounds per square inch), and produces relatively high voltages (i.e., flexing a typical foil by hand can produce several volts), allowing a simple electrical interface. Nonpiezoelectric PVDF, often termed "Kynar**," is commonly produced and used for several industrial applications, such as wire insulation and lining chemical storage tanks (it is chemically very similar to the polymer rolls commonly used in kitchens to wrap leftovers), hence it is relatively inexpensive.

Since its development[6] in the late 1960s, piezoelectric PVDF has been used in a host of applications[7,8] that exploit these and other features.[5] It has long been known to make excellent microphones and loudspeaker tweeters,[9] and is easily affixed to musical instruments (e.g., as in Richard Armin's RAAD violins and cellos[10]) to form a conformal, sensitive, and broadband contact pickup. It can be cast thicker, layered, or rolled into laminates for increased sensitivity and actuation, such as in towed array hydrophones[11] used for applications such as subsurface imaging[12] and whale census.[13] Because PVDF senses and actuates in a spatially integrated manner across a two-dimensional surface, its spatial influence and aperture shading can be determined by cutting the foil or pickup electrodes into appropriate shapes. This opens many possibilities, such as a broadband, compact acoustic directional finder,[14] sonar sensors with minimal sidelobes,[15] and a host of exciting advances in structural measurement and control.[16] Thin-gauge PVDF also exhibits high sensitivity to long infrared wavelengths (7 to 20 microns), and has appeared in heat-sensing applications such as intruder detectors and thermal imaging systems.[17] Because of this versatility, PVDF is a leading candidate for endowing many of the ubiquitous things in our environment with electromechanical transduction capabilities.

The balloon as an acoustic transducer

The balloon assembly, as designed[18,19] by K. Park and collaborators at AMP Sensors,[20] is sketched in Figure 1. It consists of a common 36-inch diameter aluminized MYLAR balloon, with a 7.5- by 10.5-inch sheet of 28 micron-wide PVDF foil adhered to the middle of one face. Both sides of the PVDF were hand-coated with a layer of approximately 20 microns of conductive silver ink. A thin-gauge (diameter approximately 30 mils) shielded cable forms a durable connection to both sides of the foil with small rivets, then is run

Figure 1 Mechanical structure of balloon-mounted transducer

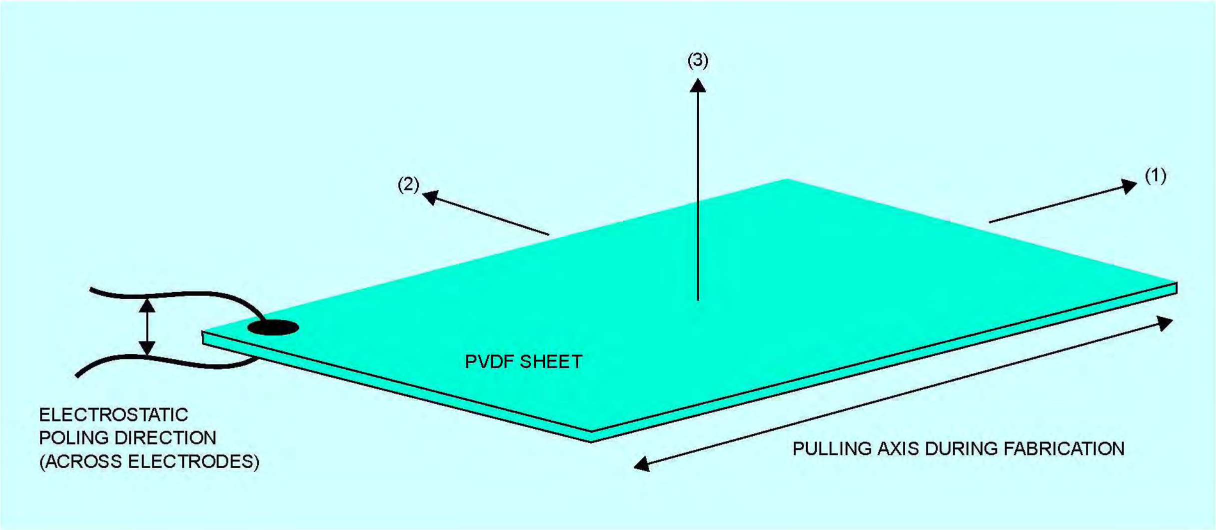


along the balloon to the base, extending through the air to a mini phone jack, which connects to the electronics. The foil is covered by a decorative aluminized decal, and the wire is likewise laminated over with aluminized tape where it traverses the balloon, rendering the transducer and cable essentially invisible to a casual inspection. Earlier versions had the PVDF foil inside the balloon, but these had difficulty maintaining secure lead attachments and could exhibit electrostatic breakdown when filled with helium and driven loudly.

Figure 1 also shows an exploded side view of the inflated balloon assembly, where we see that the inner electrode of the PVDF sheet is entirely sandwiched by its outer electrode and the balloon surface, both of which are connected by small strips of conducting copper tape and grounded to the shield of the cable (the inner electrode is insulated from the balloon by a thin sheet of double-sided adhesive foil). The inner electrode is thus reasonably well-shielded from picking up stray electromagnetic interference when used as a microphone with a simple, single-ended amplifier.

When fully inflated, the balloon assumes a roughly circular, pillow-like shape (the MYLAR stretches very little compared with a rubber balloon), with dimensions given in Figure 1. The PVDF sheet and its associated decals, foils, tapes, and wire are very light

Figure 2 Common definition of PVDF electromechanical axes



(roughly 25 grams), and a balloon inflated with helium has little difficulty lifting this mass, pulling on the cable (which also acts as tether) with a force of approximately 40 grams.

PVDF foil is characterized by a triad of piezoelectric coefficients, which express the relationship between charge presented across the foil vs strain along the three mechanical axes and arise from the alignment of the crystalline fragments and electric dipoles induced during the manufacturing process. The coefficients are expressed as d_{ij}, where "i" is the axis across which charge is measured or applied (here always in thickness, as fixed by the electrode configuration), and "j" denotes the axis of mechanical strain, as respectively measured or produced. These axes are conventionally assigned the numeric designations shown in Figure 2. The coefficients normal to the surface (d_{33}) and along the fabricated drawing direction (d_{31}) are generally of similar order;[5] e.g., $d_{31} \approx 23$ pC/N (picocoulombs per newton), $d_{33} \approx -33$ pC/N. For common uniaxial film, however, the coefficient normal to these (d_{32}) is nearly an order of magnitude smaller, indicating that most piezoelectric response occurs when the foil is compressed in thickness or stretched along the draw direction. When used as a mechanical output device, the net change in the foil size is proportional to the product of the applied voltage, the relevant d_{3j} coefficient, the inverse of foil thickness, and the length of the foil along the j axis; a similar relation applies when using the foil as a sensor.[5] Assuming an alternating current potential of ± 100 volts applied across the foil used in the balloon, we thus expect corresponding mechanical cycling to range between ± 3 nanometers in thickness (3), ± 20 microns in the draw direction (1), and ± 2 microns in the orthogonal direction (2), as labeled in Figure 2.

Because of these small deflections, a flat 7- by 10-inch sheet of foil vibrating alone in this fashion is an inefficient radiator, hence forms a soft, "tinny," and unimpressive sound source. Its performance as a tweeter can be improved by bending it into a cylindrical dome[9] (whereby the dominant d_{31} vibration in the plane of the foil is converted into motion normal to the foil, generating a better impedance match to the air), or attaching it to an acoustic radiator. In addition to supporting and levitating the PVDF sheet, the balloon provides these very important functions. Much like the way in which the wooden box of a violin acts as a resonator and radiator to color and project the modest vibration of the strings,[21] the structural and acoustic peaks in the balloon formant provide greatly enhanced audio response at lower frequencies (forming a much less brittle sound), and the larger balloon area acts as a sounding board to form a much better impedance match and more efficient acoustic source. The performance of the PVDF/balloon acoustic system is examined in more detail when audio tests are presented and discussed later in this paper.

Electronics and signal processing for the interactive balloon system

Figure 3 shows a block diagram of the electronics that were used with the balloon. The circuitry and operational detail are described more completely elsewhere.[22]

The heart of the audio record and playback system is an ISD1020A integrated circuit[23] from Integrated Storage Devices (ISD). This device is able to store up to 20 seconds of 2.7 kHz (kilohertz) audio with roughly 8 bits of resolution in an on-chip nonvolatile analog memory. Depending on how the user has set the programming switches that determine the mode of the 2-bit address counter, the ISD memory is treated as containing 1, 2, or 4 separate audio messages, which can be recorded from an on-card electret microphone, an external line-level audio source, or the PVDF balloon itself.

Output signals from the ISD1020A or external audio input are amplified, buffered, stepped up with an on-card transformer, then applied to the PVDF (this is described further with Figure 4). Before reaching the output drivers, these signals are high-pass filtered with a cutoff at 100 Hz (hertz), which prevents power from being wasted at low frequencies, where the transformer is inefficient and the PVDF has little acoustic response.

Signals coming back from the PVDF are amplified in a high-impedance preamplifier. A diode decoupling network (also discussed with Figure 4) protects this preamplifier from the high voltages on the PVDF (e.g., 100 volts) when it is being driven as a speaker. As noted in Figure 3, this preamplifier has a first-order high-pass response, reaching a gain of 45 dB (decibels) in the vicinity of 1.5 kHz. The reduction of gain at lower frequencies attenuates much of the dominant ringing in the acoustic response of the balloon and removes large signals coming from slow changes in mechanical stress as the balloon sways in the air. A very intelligible voice-quality signal is produced after this equalization. To attain sensitivity to low-level sounds, an additional adjustable gain stage is added to the front-end preamplifier.

In the usual mode of operation, the balloon waits until it detects a significantly loud sound. It then arms itself, waits until the sound stops (drops below threshold) for a significant period, then plays one of the recorded messages. This can create problems in noisy surroundings (such as a crowded room), where the background sound never stops, inhibiting the playback from triggering. The envelope follower and direct-current-blocking high-pass filter were added to the circuitry to alleviate this problem. The envelope follower rectifies and filters the audio coming from the balloon, detecting the audio amplitude, as shown in Figure 3. Continuous background noise thus produces a slowly changing direct-current bias, atop which sit the louder transient signals of someone nearby addressing the balloon. This bias is stripped away by the high-pass filter, which slowly ($\tau = 5$ seconds) adapts to the ambient room background, creating the effect of a floating trigger threshold. In certain situations, this may be undesirable, hence this feature can be disabled by the trigger-level mode switch.

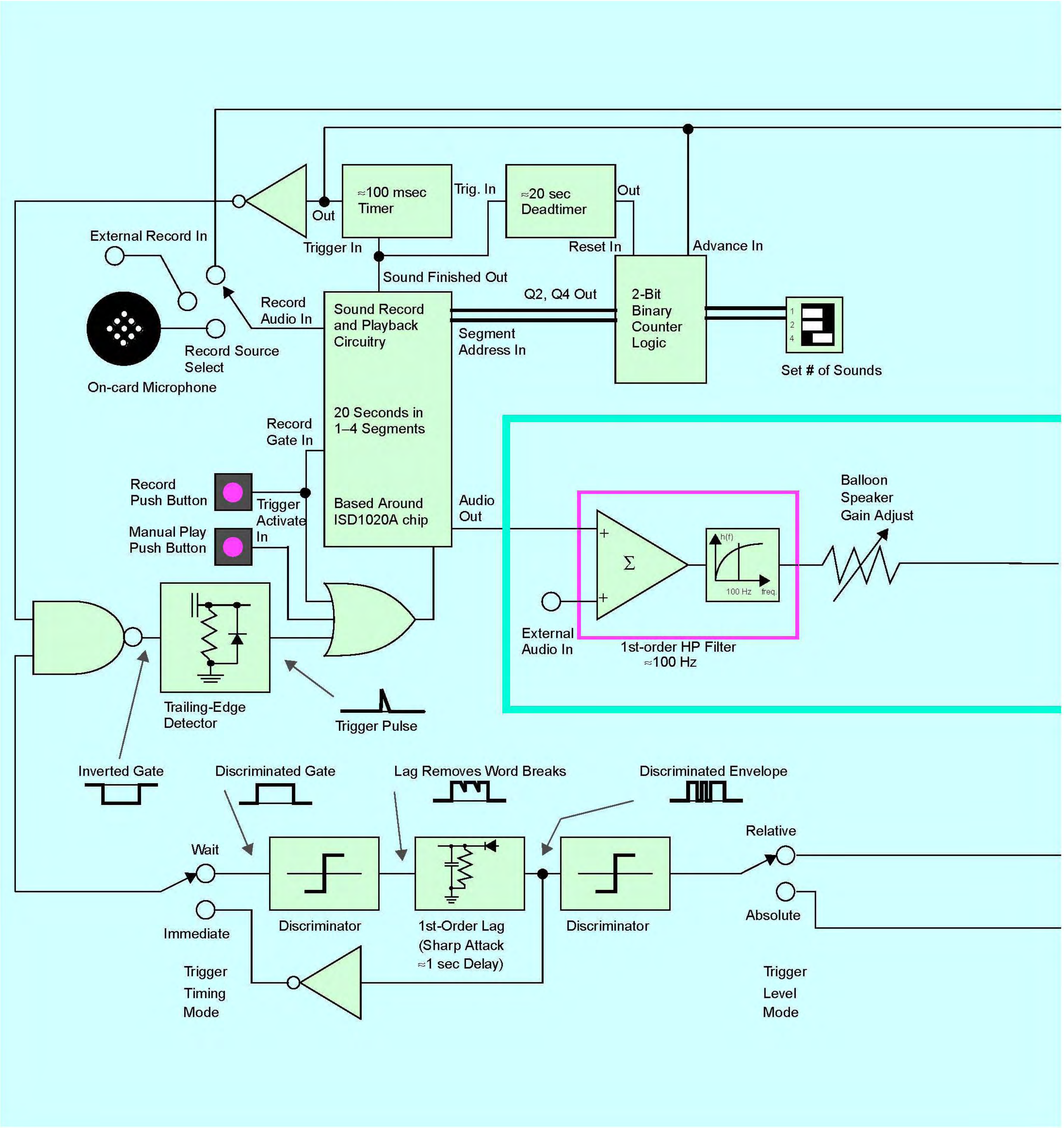
As seen in Figure 3, the word breaks and brief pauses from continuous speech are still present in this signal. The discriminators and lag circuit work to smooth over these brief stops and produce a gate that is asserted until the user stops talking. An impulse is produced upon the trailing edge of this gate, which triggers the ISD1020A to play a sound. The "aggressiveness" of interactivity is controlled by the time constant of the first order lag. If it is too fast, it will tend to interrupt the user. The units produced at the Media Lab are set to perform conservatively; the balloon waits about one-half second after the user finishes talking before responding.

In order to prevent reverberation remaining after the balloon finishes talking from promptly setting it off again, triggering is inhibited for 100 milliseconds after the balloon stops playback; the background suppression filter is also reset during this interval to recover from having saturated while the balloon was driven.

Because the counter is advanced after each balloon response, the stored messages are played back in sequential order. If the balloon is not triggered for a substantial interval (about 20 seconds), a timer resets the counter to reply with the first message, which thus acts as an introductory greeting.

Figure 4 presents a closer look at the conditioning circuitry used to interface with the PVDF. The equivalent circuit for the 7- by 10-inch sheet of PVDF foil used on the balloon is given at top left; when driven as a speaker, the foil appears as a 200 nanofarad (nf) load, yielding a reactive impedance of 800 ohms at 1 kHz. The on-card 1:10 transformer drops this to the vicinity of 8 ohms and boosts the PVDF drive voltage up to the

Figure 3 Block diagram of balloon system electronics



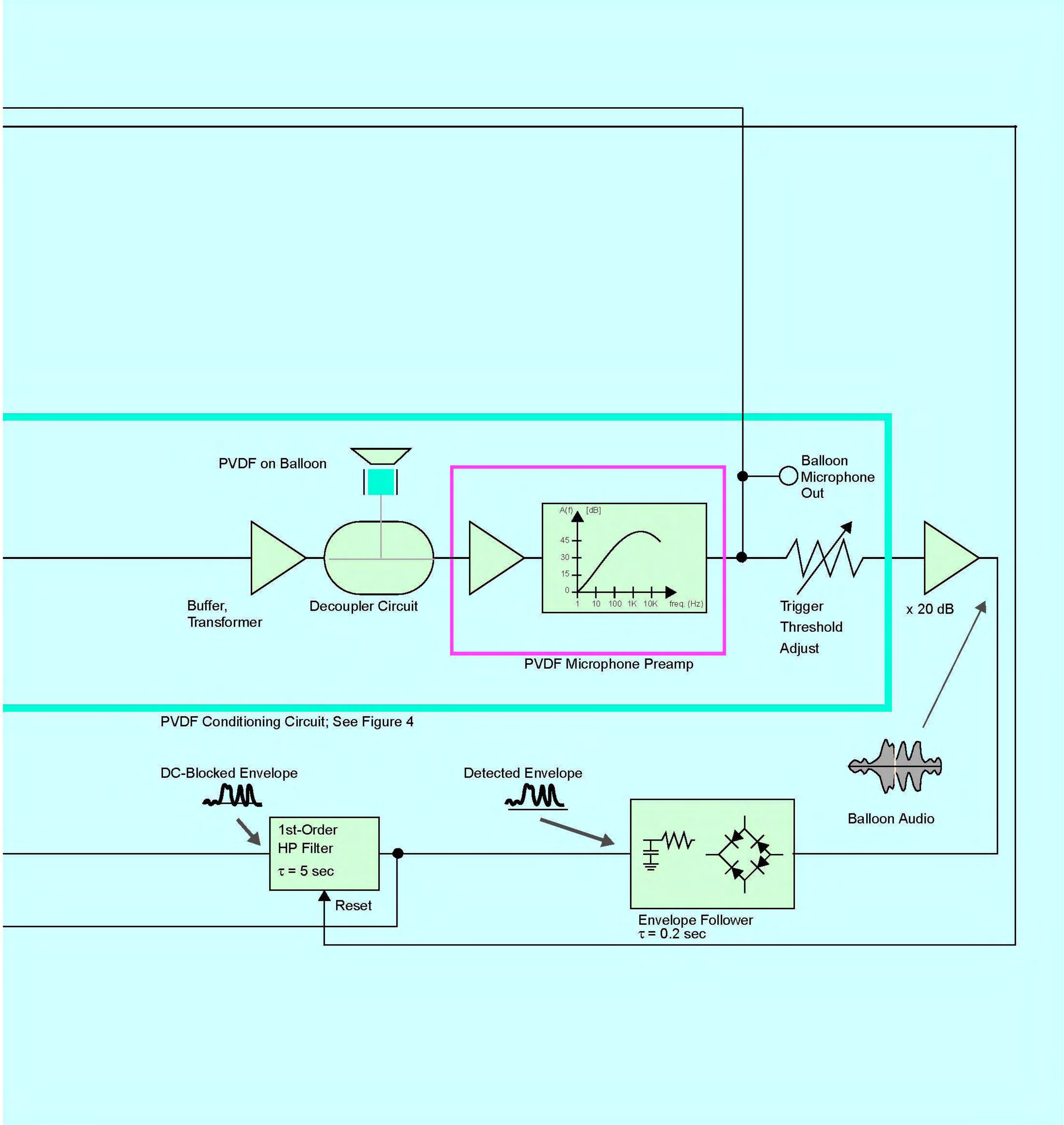
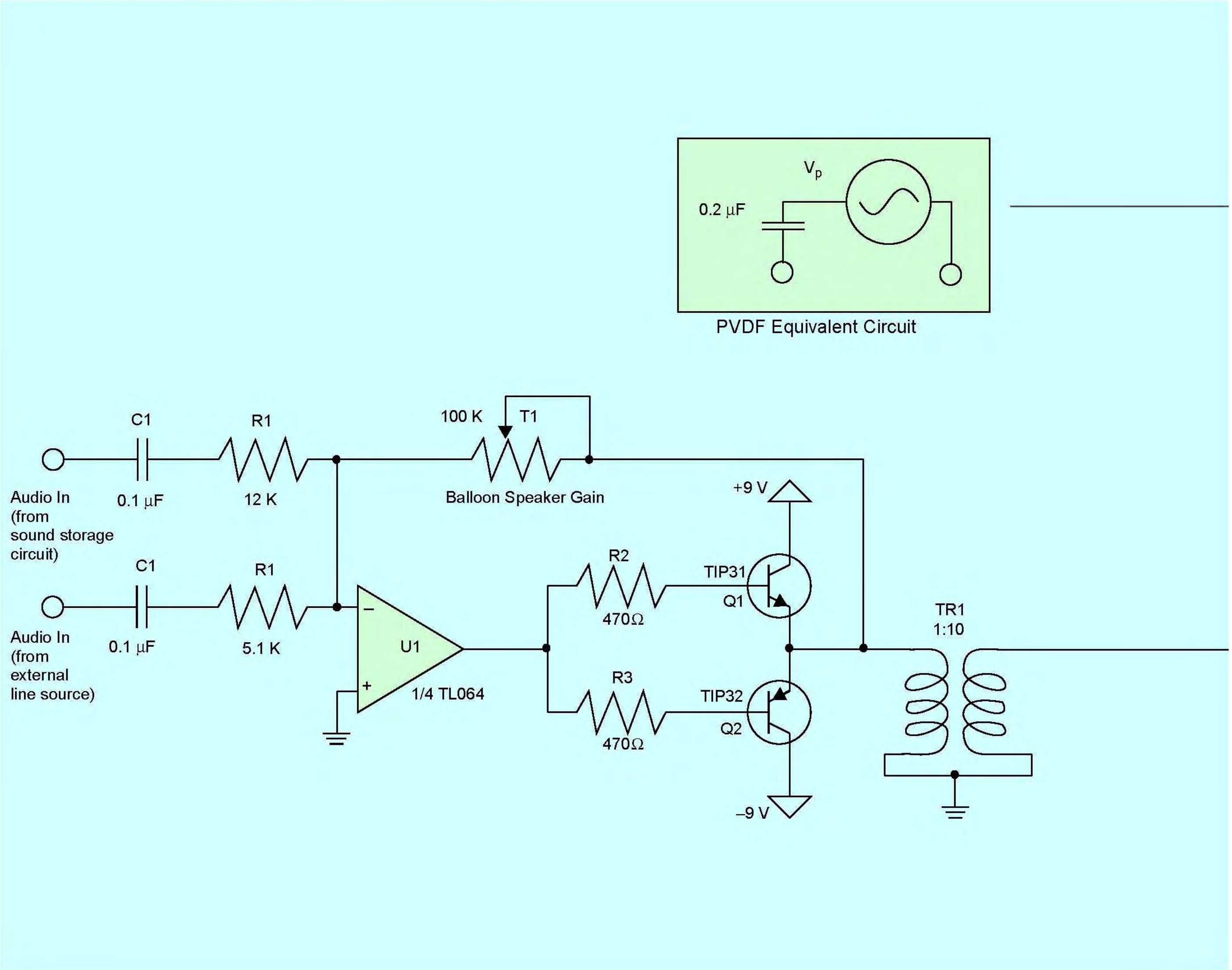
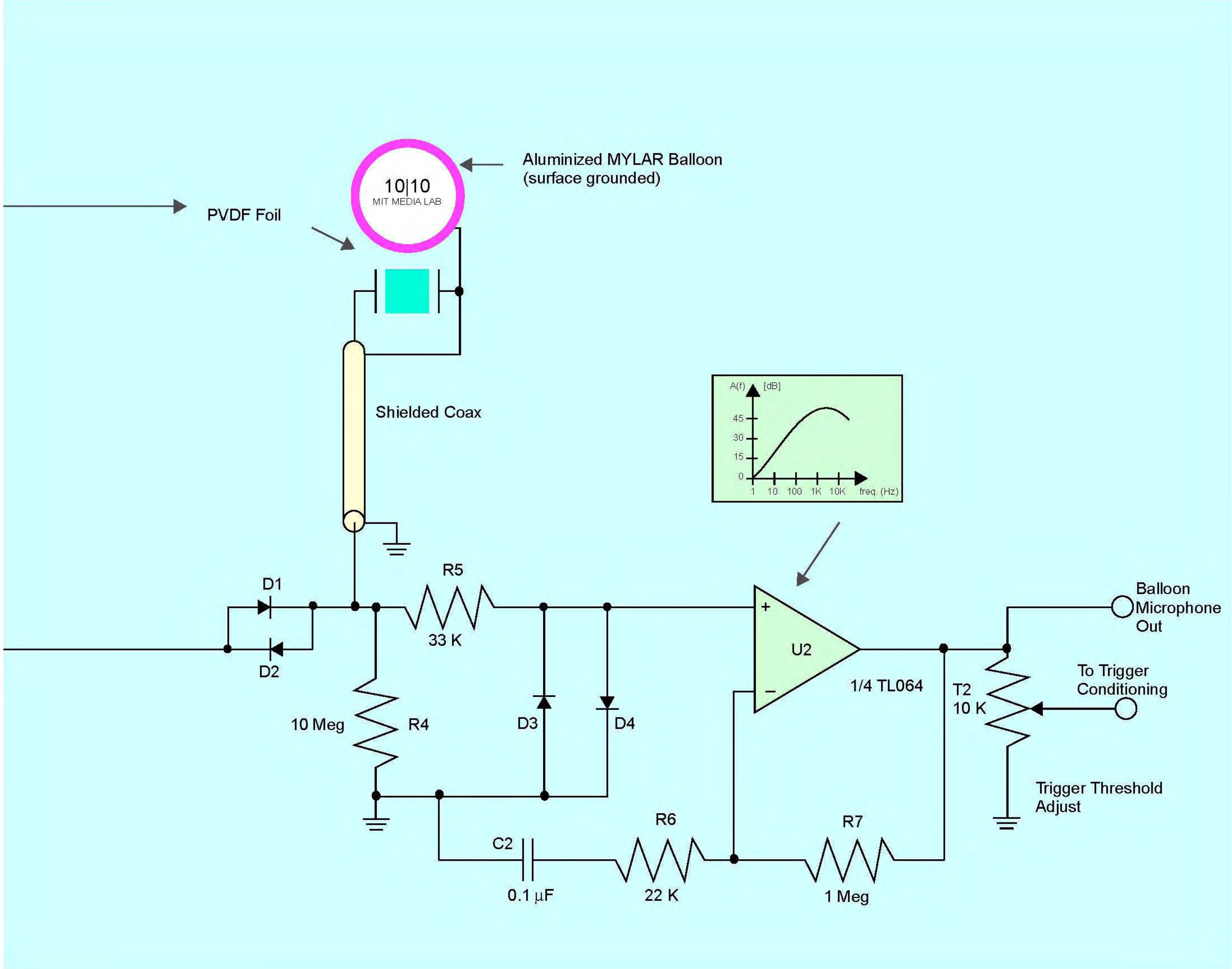

PVDF on Balloon
Balloon Microphone Out
A(f)
[dB]
45
30
15
0
1
10
100
1K
10K
freq. (Hz)
Buffer, Transformer
Decoupler Circuit
Trigger Threshold Adjust
x 20 dB
PVDF Microphone Preamp
PVDF Conditioning Circuit; See Figure 4
DC-Blocked Envelope
Detected Envelope
1st-Order HP Filter
τ = 5 sec
Reset
Balloon Audio
Envelope Follower
τ = 0.2 sec

Figure 4 PVDF signal conditioning and interface hardware



level of 100 volts peak-to-peak to gain efficiency. To reduce quiescent power, the push-pull driver is not biased for removing crossover distortion, which can hardly be noticed in this system.

Diodes D1 and D2 enable the balloon to be used both as a speaker and microphone. When driven as a speaker, the 600 mV (millivolt) diode drops are negligible compared to the 100 volt PVDF drive after the transformer; they essentially act as a wire. When the PVDF is undriven, however, the foil returns to ground via R4, hence D1 and D2 effectively become open circuits (the raw PVDF response to conversational audio is well below the 600 mV diode clip), allowing the PVDF microphone signals to be amplified by the high-impedance JFET (junction field-effect transistor) operational amplifier U2 (D3 and D4 protect U2 when the balloon is driven at high voltage). Because of the C2, R6 network in its feedback circuit, amplifier U2 acts as a first-order high-pass filter, with gain increasing from 0 through roughly 50 dB for frequencies between 1 Hz and 1.5 kHz, as plotted in the figure.



This type of frequency-biased front-end amplifier is often used[24] to avoid large-amplitude, low-frequency background from the transducer mechanics when conditioning PVDF signals for higher frequency operation.

Figure 5 shows a photograph of a completed balloon tethered to its readout electronics. The system ran off a pair of standard 9-volt rectangular batteries, and pulled under 5 mA (milliamperes) in its quiescent state while listening for triggers, allowing it to remain active for days. With a pair of alkaline batteries, it is capable of maintaining about four hours of continuous sound production. In addition to supplying ample power capacity, the batteries also provided enough ballast to prevent the balloons from floating away.

Acoustic performance and analysis

A MYLAR balloon excited by an attached piece of PVDF foil is a complicated structural/acoustic system. In order to get a quantitative glimpse at its sonic performance, the balloons were tested in an acoustically

Figure 5 Photograph of a complete interactive balloon system

damped and isolated music practice room, as an approximation to an anechoic chamber. Measurements were taken with a Bruel and Kjaer (B&K) Type 4133 precision microphone calibrated with a B&K Type 4220 source and conditioned with a B&K Type 2604 preamplifier. An Arbitrary Waveform Generator from Hewlett-Packard (the HP 33120A) was used to generate white noise and sinewaves, and spectral data was acquired with an HP 3560A Dynamic Signal Analyzer. A hand-held Yu-Fing YF-20 Sound Level Meter monitored the audio levels around the balloon.

When playing back voice samples, a fully inflated balloon can be reasonably loud; A-weighted[25] RMS (root mean square) sound pressures averaging between 70 and 80 dB and peaks approaching 90 dB (with regard to 20 micropascals, as conventional with in-air acoustics) were measured a foot away from the balloon's surface.

Figure 6 shows the 0–10 kHz pressure spectrum levels (PSLs) for three systems, all driven through the electronics shown in Figure 4. As labeled, these are a fully inflated balloon (taut surface, ringing like a tuned drum when hit), a partially inflated balloon (soft surface, no ringing when hit), and the driving foil suspended alone without the balloon attached (i.e., the PVDF strip, decal, and piece of MYLAR balloon foil behind the PVDF). Two volts (RMS) of white noise was input to these systems via the external audio tap shown in Figure 4, and their acoustic outputs were monitored with the calibrated microphone located a foot away from the center of the PVDF strip.

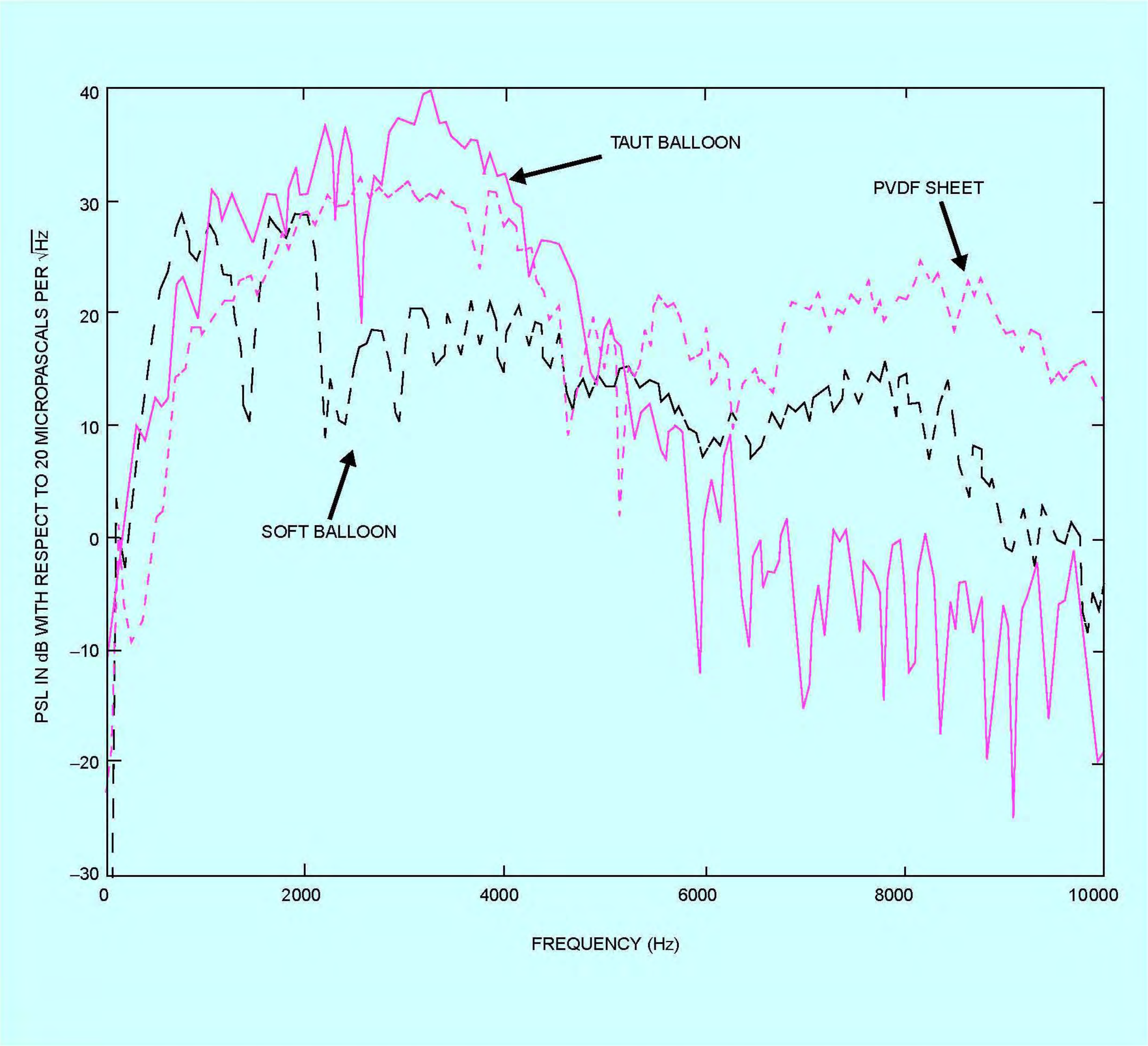
As can be noted by the multiplicity of peaks in Figure 6, the balloon is a nontrivial structural/acoustic system. At lower frequencies (under 500 Hz), the sonic wavelength in helium (triple that of air) grows significantly larger than the smallest balloon dimension, thus the balloon can be analyzed as a classic lumped acoustic resonator,[26] such as a bubble.[27] The transient response of the balloon is dominated by these low-frequency resonant modes and their inherent damping, which can be plainly heard as a slow-decay ringing when a balloon is struck (in the full, "taut" balloon used in these tests, there was a clear pair of such resonances near 50 and 100 Hz).

At roughly 700 Hz, a half-wave fits across the diameter of the helium-filled balloon, and at roughly 1500 Hz, a half-wave fits between front and back faces; in these regions, the balloon begins acting as a resonant cavity. Because of the balloon taper (it is quite oblate, not spherical), the modal structure will be complicated. Together with flexural modes being excited in the MYLAR membrane (such as seen in drumheads[28]), one would expect lots of peaks and nulls in the response, such as seen in Figure 6.

Over the frequency range most relevant for reproducing speech (500 Hz to 5 kHz), the fully inflated balloon produces significantly more output than the other cases. At higher frequencies, this system becomes somewhat directional, dissipative, and a less efficient resonator. At lower frequencies, the PVDF provides a poor impedance match because of its limited displacement (plus the balloon drive electronics roll off below 200 Hz), hence the balloon is not driven efficiently, and little response is seen, despite the strong lumped poles at 50 and 100 Hz.

The balloon must be tightly inflated to make a good sound projector, as evidenced by the inferior overall response of the "soft" balloon. Here, the membrane resonances are less pronounced, removing much of the response between 2 and 5 kHz. The large structures below 2 kHz, however, are in the regions where the balloon volume forms a resonant cavity, as dis-

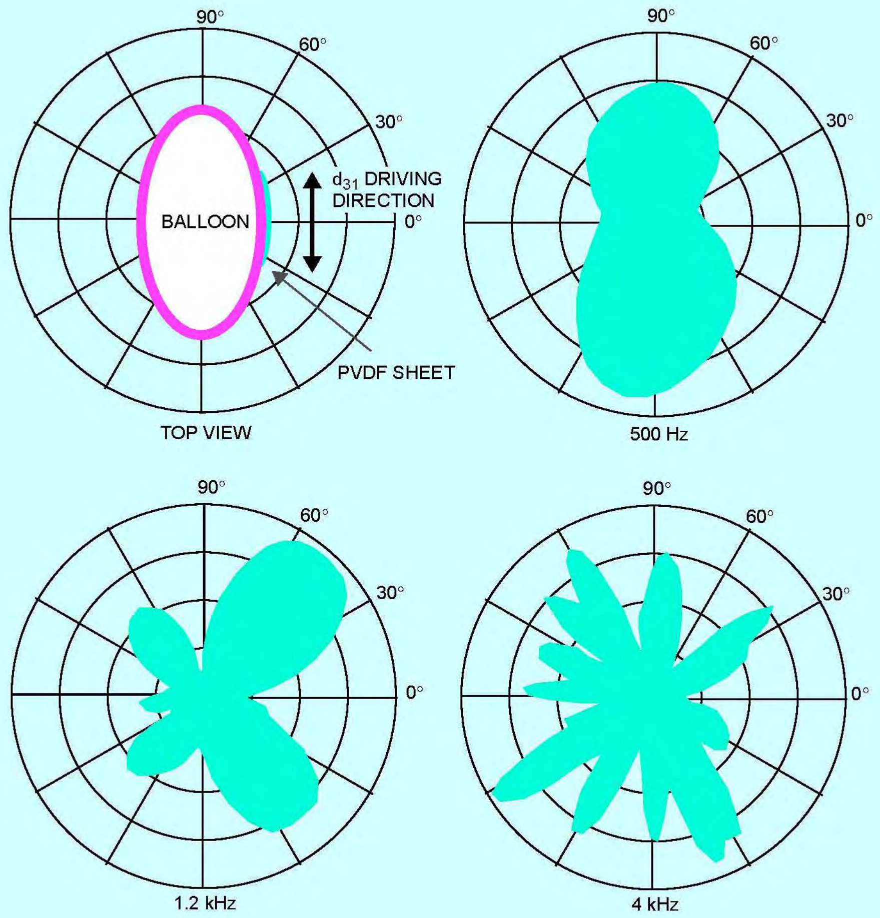
Figure 6 **Pressure spectra of taut balloon, soft balloon, and suspended foil sheet, as measured one foot away from the center of the driven PVDF surface**



cussed previously. The soft balloon seems to be the best performer at low frequencies; this measurement, however, is somewhat biased, since the taut balloon directs most of its lower frequency sound away from its center axis (where the data were taken), as illustrated in Figure 7.

The PVDF sheet tested in Figure 6 was supported at top center by a wire, and freely drooped at either edge. As can be plainly seen, its high-frequency response was superior (high-performance tweeters are made from domed sheets of PVDF[9]), although it was very directional, projecting most sound forward toward the microphone. The unattached foil is a much smaller radiator, however, and without the balloon formants to accentuate the low-end response, there was little emission below 1 kHz, producing a very "tinny" sound. The performance of the PVDF sheet surpassed that of the soft balloon beyond 2 kHz; this is most probably because it was curved by the hang-

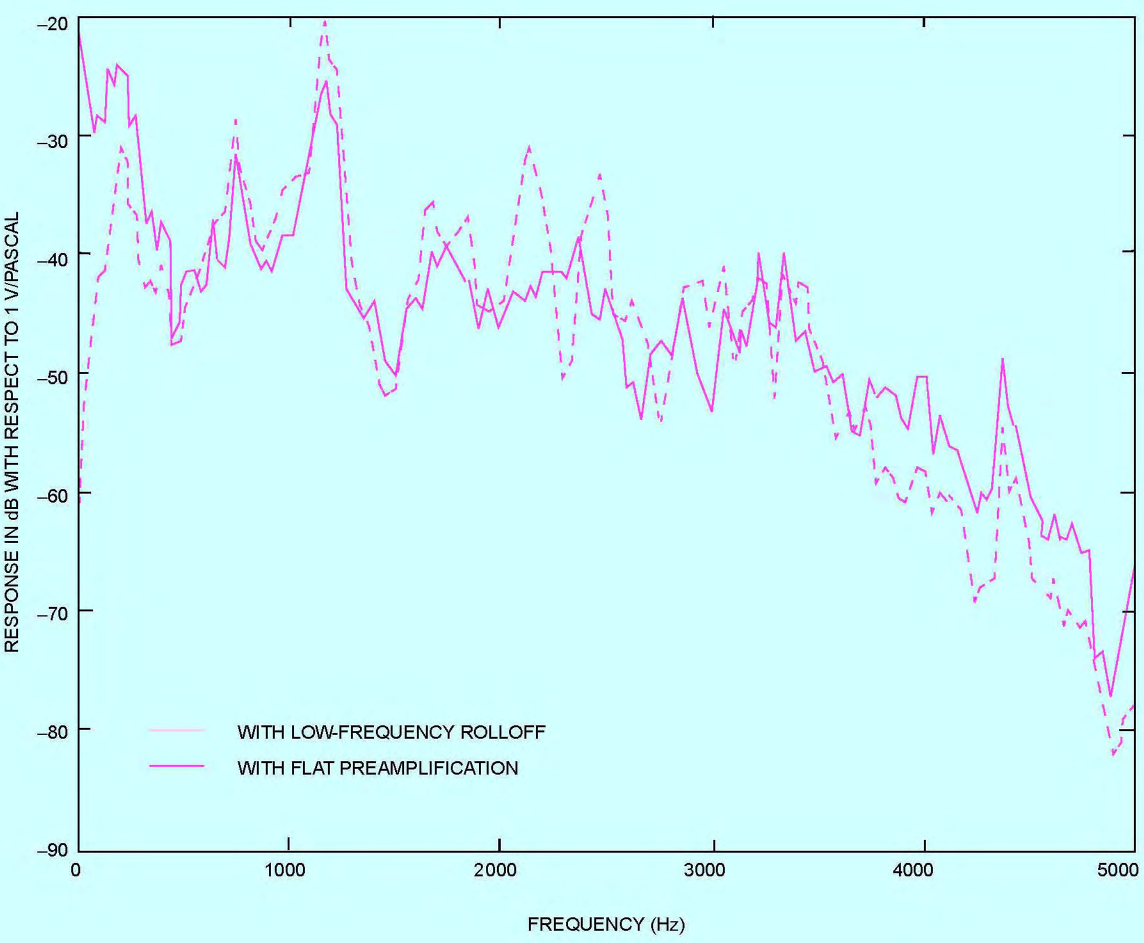
Figure 7 Horizontal, near-field intensity pattern of taut balloon measured at three frequencies



ing suspension, forming a better impedance match to the air than the soft balloon (where the PVDF was held flat).

When listening to a balloon making sound, a pronounced angular dependence can be noticed in the sound levels. Examining this in more detail, Figure 7 shows a rough measurement of the near-field sound intensity produced by the taut balloon in its horizontal midplane at three different frequencies. These data were collected by placing the microphone close (roughly 8 inches) to the center of the balloon surface, then spinning the balloon at a uniform rate around its cord (using a display motor running at 2 revolutions per minute), while continually sampling the amplitude envelope detected at the microphone. Figure 7 is plotted in polar coordinates; the drawing at upper left shows the angular reference. Although the display

Figure 8 **Sensitivity of balloon pickup with and without low-frequency rolloff**



motor appeared to spin the balloon smoothly, and the near-field acoustic measurement is dominated by the direct sound path, imperfections in the balloon rotation and reflections from the room surfaces exert some influence on these measurements, thus these data are analyzed only for general trends.

At 500 Hz, the intensity pattern assumes a rough peanut shape, with the beginnings of a null forming near the center and maxima near plus and minus 90 degrees. The shorter wavelength at 1.2 kHz introduces more interference effects, plus a higher-order modal behavior is suggested, as the angular response assumes a lobed structure. At this point, significant phase differences can be detected over the balloon surface; the lobes on opposite sides of the balloon (reflected across the 90 degree axis) are oscillating in opposing phase, indicating dipoles across the narrow balloon diameter. At 4 kHz, the directionality becomes very complex, suggesting a superposition of many different modes that correspond to excited acoustic and structural degrees of freedom. In general, the sound at most speech frequencies is seen to emanate away from broadside (0 and 180 degrees) and out toward the edges, an effect quickly noticed when hearing the balloon enunciate.

Figure 8 shows the frequency response of the taut balloon when used as a pickup. In this test, the balloon was radiated white noise from a Snell Acoustics Type EII Loudspeaker. The balloon pickup spectrum was recorded, then normalized by a reference noise spectrum detected by placing the calibrated microphone at the balloon position, in order to compensate for the loudspeaker's frequency response. Two curves are shown; one using a flat-response balloon preamplifier and another using the high-pass filtering front end shown in Figure 4. The low-frequency rolloff in the latter curve is obvious below 500 Hz; this nicely attenuated the strong lumped resonances, which were easily excited by transients. Otherwise, many peaks are seen, arising from the complicated acoustic structure discussed above. The input response rolls off after 3 kHz in a similar fashion to the taut balloon's output response in Figure 6, thus it is well matched to the voice spectrum. These curves show the sensitivity of the balloon transducer in dB (with respect to 1 volt per Pascal), and are compensated for a flat 45 dB gain from the balloon preamplifier (no spectral response is included), in order that they reference the level expected at the transducer.

Applications

Over 60 of these balloon systems were manufactured and distributed to various Media Lab researchers for the open house at the Laboratory's tenth anniversary, resulting in many innovative applications. The most common was an interactive "oracle" outside a laboratory, hawking the research pursued within. The balloon would hear people walking up, prompt them with its introductory message, and produce its remaining lines upon further questioning.

When a group of balloons can hear and speak to one another, they spontaneously interact. A pair of balloons tends to work as an astable multivibrator; since they wait for their partner to finish before speaking themselves, they produce an often amusing conversation. This property was exploited in several installations at the open house; one pair of balloons played complementary bars of *Dueling Banjos*,[29] and another pair perpetually screamed "cheeseburger" and "Pepsi**" at one another. The largest installation was a cluster of four balloons, which were programmed with excerpts of Marvin Minsky reading from his book *Society of Mind*.[30] Until their batteries ran out, the balloons piped these samples at one another in a shifting, pseudorandom order. Their behavior was like a group of crickets; when nearby people were making steady noise, they fell dormant, resuming their calls once it was again silent.

The balloons were also applied as speakers for external audio sources. A group of nine were wired in parallel and distributed across the atrium of the auditorium where the anniversary symposium was held, forming a "concealed" public address system. Some people used them as a festive audio output device for computers running different demos. One of the most unusual[31] involved two computers playing a game of "Battleship" with one another, communicating via coded bursts of audio sent across a pair of balloons.

The amount of background sound varied from place to place across the laboratory, and was often significant. Nonetheless, the noise compensation circuitry worked, and the balloons always triggered, thus were able to perform their duties.

Conclusions

With a piece of lightweight PVDF foil and some simple electronics, we have turned a common party balloon into something that can listen, talk, and interact. In addition to its novelty value, the PVDF balloon actually functions as a good voice transducer. The balloon significantly improves the impedance match of the PVDF strip to air, producing an efficient radiator and microphone at speech frequencies. Simple linear filtering is able to suppress the low-frequency balloon reverberation adequately for voice intelligibility when listening through the PVDF.

This project has focused on the transducer, not the application. A logical next step is to augment the analog front end with digital processing to enable speech recognition and synthesis, plus provide an interface into a digital network. But the simple and surprisingly successful system described here, offering helpful sensing and communication where it is least expected, already gives us a glimpse into the future through a "thing that thinks."

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**Trademark or registered trademark of E. I. Du Pont de Nemours & Co., Dexter, Inc., or PepsiCo, Inc.

Cited references and notes

1. L. Creme and K. Godley, "I Pity Inanimate Objects," from *Freeze Frame*, PD-1-6257, Polydor Records (1979).
2. See: http://ttt.www.media.mit.edu
3. L. C. Kupferberg and R. H. Tancrell, "Poly(Vinylidene Fluoride): Properties and Application in Acoustic Sensors," *U.S. Navy Journal of Underwater Acoustics* **41**, No. 1, 7–28 (January 1991).
4. G. M. Sessler, "Piezoelectricity in Polyvinylidenefluoride," *Journal of the Acoustical Society of America* **70**, No. 6, 1596–1668 (December 1981).
5. *Piezo Film Sensors Technical Manual*, Document 65751, AMP Sensors Incorporated, Valley Forge, PA (1993).
6. H. Kawai, "The Piezoelectricity of Poly(Vinylidene Fluoride)," *Japan Journal of Applied Physics* **8**, 975–976 (1969).
7. B. H. Carlisle, "Piezoelectric Plastics Promise New Sensors," *Machine Design* **58**, No. 25, 105–110 (October 23, 1986).
8. I. Amato, "Fantastic Plastic," *Science News* **136**, No. 21, 328–329 (November 18, 1989).
9. J. Klapholz, "Polymer Film for Transducers," *db Magazine*, 27–32 (November-December 1985).
10. J. L. Duperray, "Les Nouveaux Violons," *Diapason*, No. 296, 88–89 (July/August 1984).
11. H. L. W. Chan, A. H. Ramelan, I. L. Guy, and D. C. Price, "VF_2/VF_3 Copolymer Line Hydrophone and Line Hydrophone Array for Ultrasonic Measurement," *Sensors and Materials* **3**, No. 1, 49–60 (1991).
12. D. P. Marschall, R. E. Pearce, and R. A. Marschall, "Polar Seismic Surveying with Towed Hydrophone Array," *Sea Technology* **37**, No. 4, 45 (September 1994).
13. C. W. Clark and C. H. Spikes, "Whales '95—Revolutionizing Marine Mammal Monitoring Technology," *Sea Technology* **37**, No. 4, 49–56 (April 1996).
14. S. Burke, J. Paradiso, T. Bailey, and R. Ciliberto, "Monopulse Piezopolymer Sonar Sensor," submitted to *Journal of the Acoustical Society of America* (1996).
15. W. J. Hughes and C. W. Allen, "A Shaped PVDF Hydrophone for Producing Low Sidelobe Beampatterns," *Proceedings of the 1992 Symposium on Autonomous Underwater Vehicle Technology* (AUV '92), 219–223, IEEE Press, New York (1992).
16. S. Burke and J. Hubbard, Jr., "Distributed Transducers for Structural Measurement and Control," Volume 36 of *Advances in Control and Dynamic Systems*, C. T. Leondes, Editor (1990), pp. 223–273.
17. E. Tom, "Polymer Film Arrays in Pyroelectric Applications," *Sensors* **11**, No. 9, 75–77 (September 1994).
18. K. T. Park and P. F. Radice, *Electroacoustic Novelties*, U.S. Patent No. 5,309,519 (May 3, 1994).
19. P. F. Radice, *Air Buoyant Piezoelectric Polymeric Film Microphone*, U.S. Patent No. 4,843,275 (June 27, 1989).
20. Flexible Film Products Group, AMP Incorporated, Valley Forge, PA.
21. L. Cremer, *The Physics of the Violin*, MIT Press, Cambridge, MA (1984).
22. J. A. Paradiso, "Using the Interactive Piezo Balloon System," internal memo, Physics and Media Group, MIT Media Laboratory (October 5, 1995).
23. T. Cantrell, "Talking Chips," *Circuit Cellar INK, The Computer Applications Journal*, No. 36, 62–69 (July 1993).
24. C. Kitchin and S. Wurcer, "New Amplifiers Provide a Fully Packaged Solution for Sonar Applications," *Analog Briefings* (Analog Devices, Inc.) 7, No. 2, 3–4 (Summer 1991).
25. A-weighting is the standard frequency weighting used in acoustics to measure the human response to moderate-level sound.
26. J. C. Huang, "Harmonic Frequency Generation by a Pulsating Resonator Sonically Excited," *IEEE Transactions on Sonics and Ultrasonics* **SU-21**, No. 2, 106–114 (April, 1974).
27. L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, *Fundamentals of Acoustics*, Third Edition, John Wiley & Sons, Inc., New York (1982).
28. N. H. Fletcher and T. D. Rossing, *The Physics of Musical Instruments*, Springer-Verlag, New York (1991).
29. This musical duel, composed by Arthur Smith, was featured in the 1972 movie *Deliverance*, directed by John Boorman.
30. M. Minsky, *The Society of Mind*, Simon & Schuster, Inc., New York (1988).
31. V. Gerasimov, "Things That Talk," master's degree thesis, MIT, Cambridge, MA (February 1996).

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