The Interactive Balloon: Sensing, Actuation and Behavior in a Common Object

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Abstract

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 Lab.

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

Godley & Creme,[1] 1979

1) Introduction

The introduction of sensing, actuation, and behavior into the fabricated artifacts that surround our lives is well underway. 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 hardwired 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 coffee maker for more brew when it senses your hand approaching), life in a world saturated with such capability will be vastly different from the transitory 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 everyday objects. Several articles 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. This balloon, however, is able to converse.
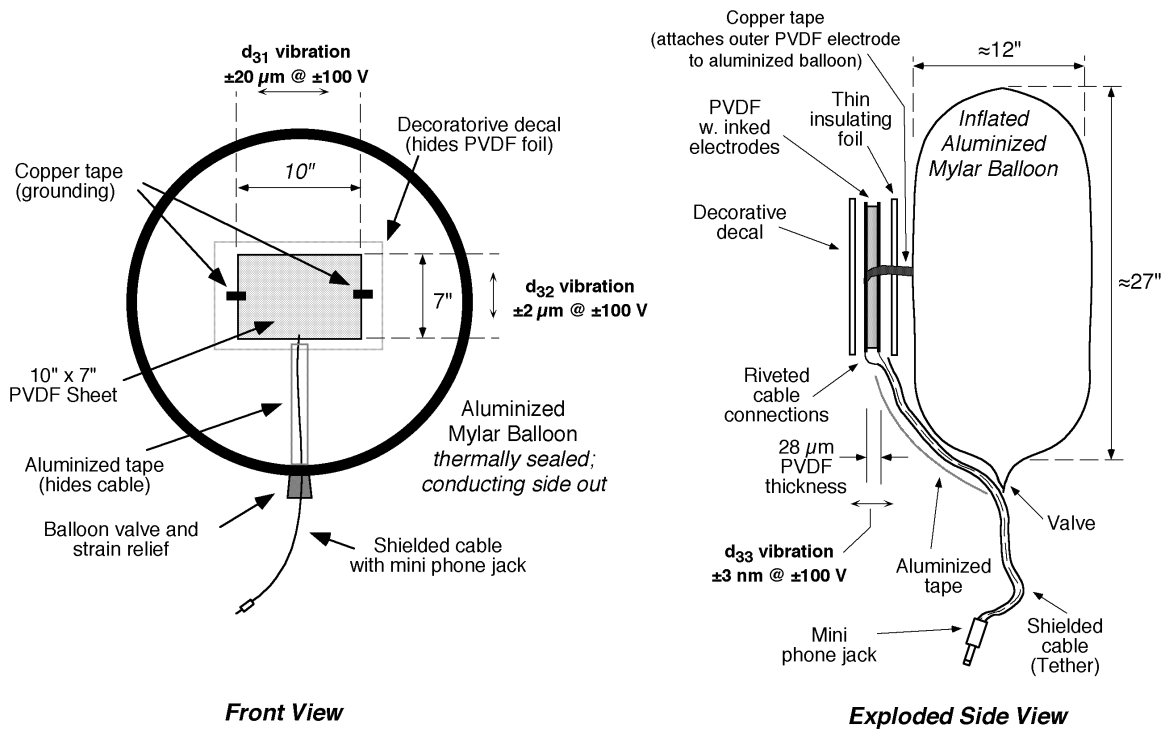
2) PVDF foil

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 manufacturingpiezoelectric 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 9-110 microns.[5] Although the foil is mechanically tough, it remains quite elastic (having a Young's modulus under 2.5 GPa), 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} - 10^6 psi), and produces relatively high voltages (i.e., flexing a typical foil by hand can produce several volts), allowing a simple electrical interface. Non-piezoelectric PVDF, often termed "Kynar$^{®}$", is commonly produced and used for several industrial applications, such as wire insulation and lining chemical storage tanks (it is very chemically similar to the polymer rolls commonly used in kitchens to wrap leftovers), hence it is relatively inexpensive.

Since its development[6] in the late 1960's, 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 the 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 2-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 direction 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 IR wavelengths (7-20 μm), and has appeared in heat-sensing applications such as intruder detectors and thermal imaging systems.[17] Because of this versatility, PVDF is a

Front View

d$_{31}$ vibration
±20 µm @ ±100 V

10"

Copper tape (grounding)

Decoratorive decal (hides PVDF foil)

d$_{32}$ vibration
±2 µm @ ±100 V

7"

10" x 7" PVDF Sheet

Aluminized tape (hides cable)

Balloon valve and strain relief

Shielded cable with mini phone jack

Aluminized Mylar Balloon
thermally sealed; conducting side out

Exploded Side View

Copper tape (attaches outer PVDF electrode to aluminized balloon)

≈12"

PVDF w. inked electrodes

Thin insulating foil

Inflated Aluminized Mylar Balloon

Decorative decal

≈27"

Riveted cable connections

28 µm PVDF thickness

d$_{33}$ vibration
±3 nm @ ±100 V

Aluminized tape

Valve

Mini phone jack

Shielded cable (Tether)

Figure 1: Mechanical structure of balloon-mounted transducer

leading candidate for endowing many of the ubiquitous things in our environment with electromechanical transduction capabilities.

3) 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 Fig. 1. It consists of a common 36" diameter aluminized mylar balloon, with a 7.5" x 10.5" 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 20 microns of conductive silver ink. A thin-gauge (Ø 30 mils) shielded cable forms a durable connection to both sides of the foil with small rivets, then is run 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.

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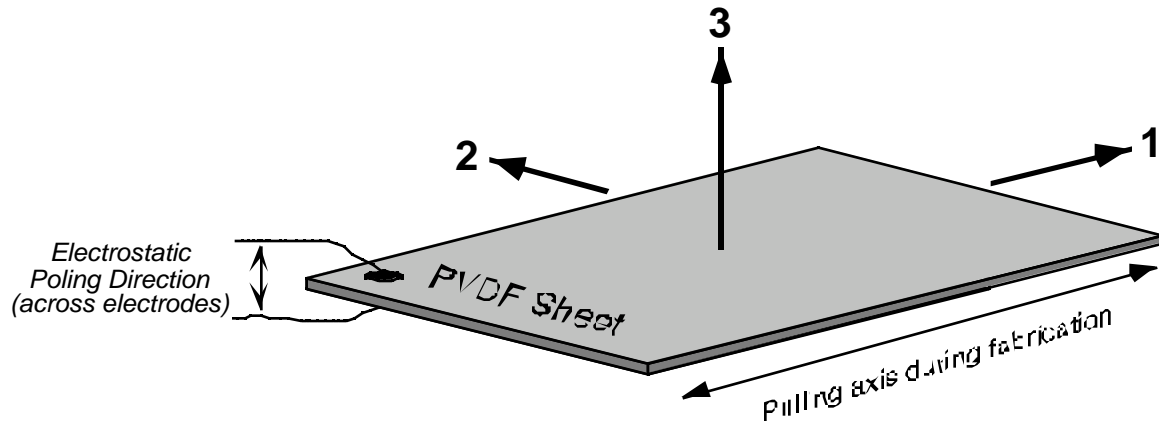
Figure 2: Common definition of PVDF electromechanical axes

Fig. 1 also shows an exploded sideview of the inflated balloon assembly, where we see that the inner electrode of the PVDF 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 PVDF electrode is thus reasonably well-shielded from stray EMI pickup 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 Fig. 1. The PVDF and its associated decals, foils, tapes, and wire are very light (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 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 Fig. 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} 23 pC/N, d_{33} -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 (V), the relevant d_{3j} coefficient, the inverse of foil thickness (1/t), and the length of the foil along the j axis (l_j); a similar relation applies when using the foil as a sensor[5]. Assuming an AC potential of ±100 volts applied across the foil used in the balloon, we thus expect corresponding mechanical cycling to range between ±3 nm in thickness, ±20 μm in the draw direction, and ±2 μm in the orthogonal direction, as labeled in Fig. 1.

Because of these small deflections, a flat 7" x 10" strip 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 to motion normal to the foil, generating a better impedance match to the air), and/or attaching it to an acoustic radiator. In addition to supporting and levitating the PVDF, 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/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.

4) 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/playback system is an ISD1020A integrated circuit[23] from Integrated Storage Devices. This device is able to store up to 20 seconds of 2.7 kHz 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 mode 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 Fig. 4). Before reaching the output drivers, these signals are high-pass filtered with a cutoff at 100 Hz, which prevents power from being wasted at low frequencies, where the transformer is inefficient and the PVDF has little acoustic response.
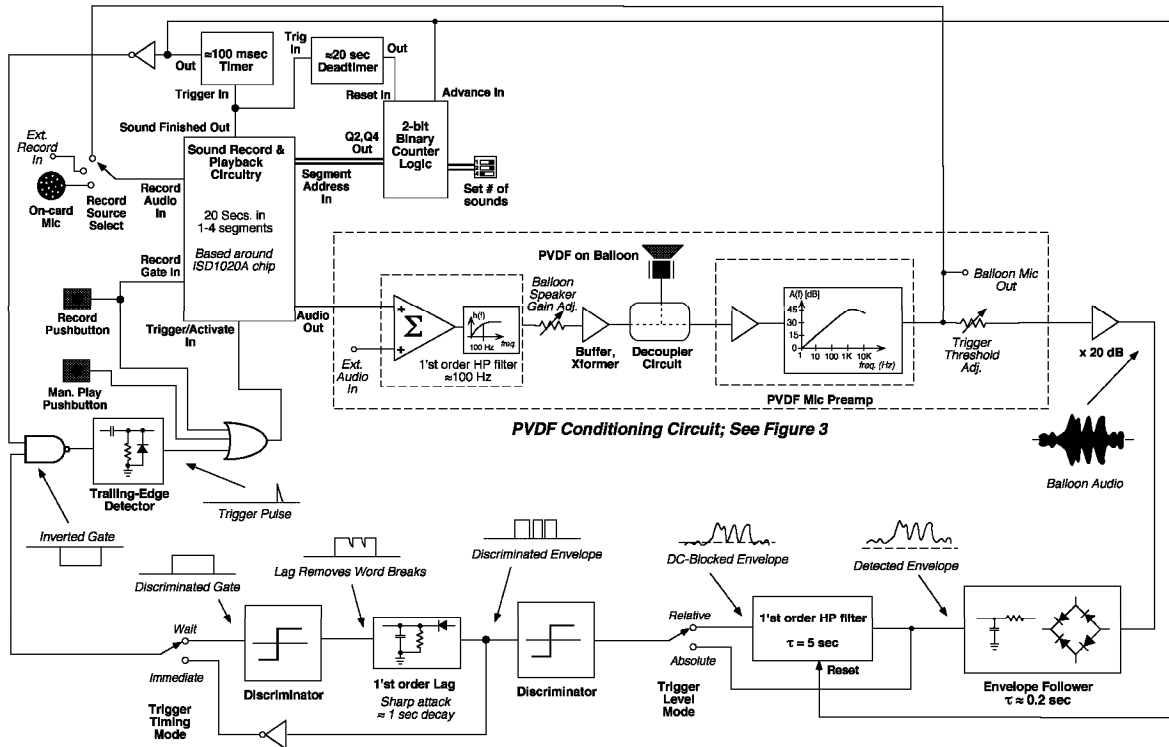
Figure 3: Block diagram of balloon system electronics

Signals coming back from the PVDF are amplified in a high-impedance preamplifier. A diode decoupling network (also discussed with Fig. 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 Fig. 3, this preamplifier has a first-order high-pass response, reaching a gain of 45 dB 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 DC-blocking highpass filter were added to this circuitry to alleviate this problem. The envelope follower rectifies and filters the audio coming from the balloon, detecting the audio amplitude, as sketched in Fig. 3. Continuous background noise thus produces a slowly changing DC bias, atop

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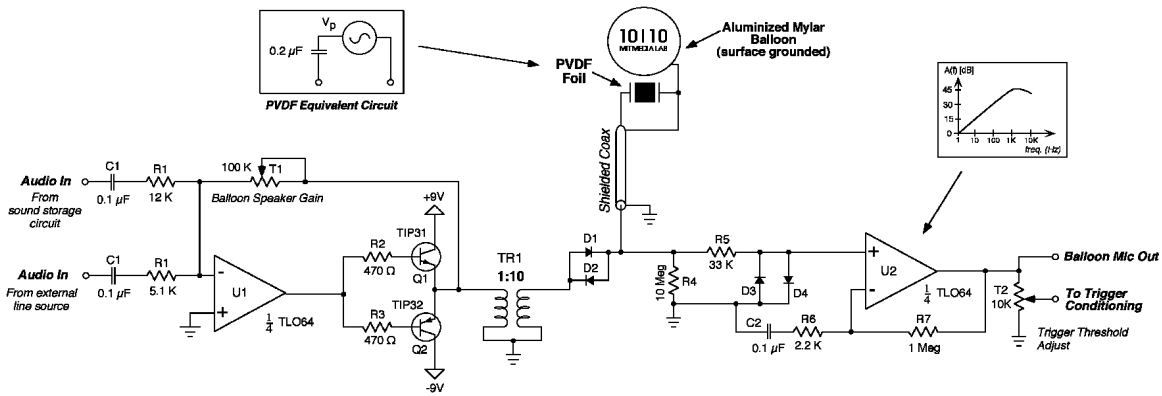
Figure 4: PVDF signal conditioning and interface hardware

which sit the louder signals of somebody nearby addressing the balloon. This bias is stripped away by the high-pass filter, which slowly (= 5 sec) 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 Fig. 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 $1/2$ 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 msec 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 (circa 20 sec), a deadtimer resets the counter to reply with the first message, which thus acts as an introductory greeting.

Fig. 4 presents a closer look at the conditioning circuitry used to interface with the PVDF. The equivalent circuit for the 7" x 10" sheet of PVDF foil used on the balloon is given at top left; when driven as a speaker, the foil appears as a 2 nanoFarad (nf) load, yielding a reactive impedance of 800   at 1 kHz. The on-card 1:10 transformer drops this to the vicinity of 8   and boosts the PVDF drive voltage up to the level of 100 volts p-p to

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Figure 5: Photograph of a complete interactive balloon system

gain efficiency. To reduce quiescent power, the push-pull driver is not biased for removing crossover distortion, which can hardly be heard 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 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 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 highpass 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 in its quiescent state while listening for triggers, allowing it to remain active for days. With a pair of alkalines, it is capable of maintaining about 4 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.

5) 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 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 RMS sound pressures averaging between 70 and 80 dB and peaks approaching 90 dB (re. 20 µPa, as conventional with in-air acoustics) were measured a foot away from the balloon's surface.

Fig. 6 shows the 0-10 kHz pressure spectrum levels (PSL's) for three systems, all driven through the electronics of Fig. 4. As labeled, these are a fully inflated balloon (taut
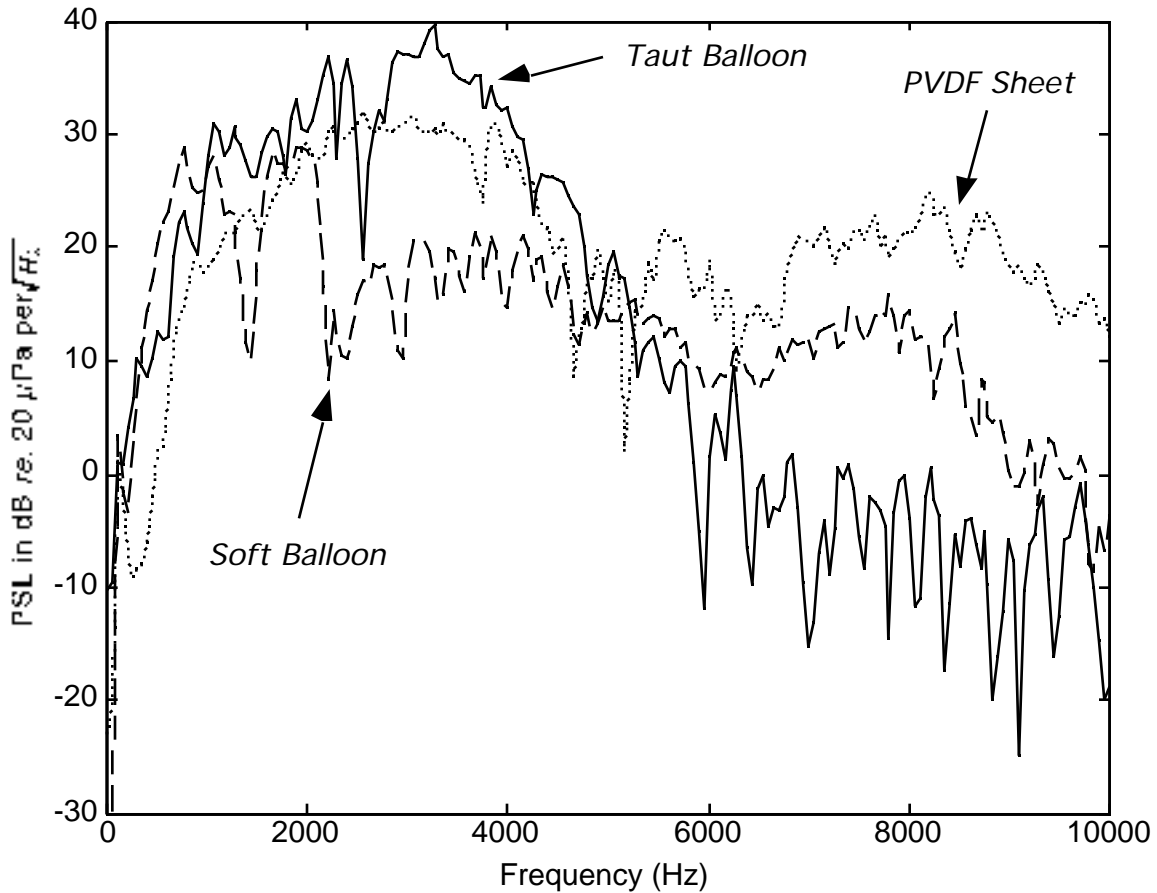
Figure 6: Pressure Spectra of taut balloon, soft balloon, and suspended foil sheet, as measured 1 foot away from the center of the driven PVDF surface

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 of Figure 4, and their acoustic outputs were monitored with the calibrated microphone located a foot away from the center of the PVDF.

As can be noted by the multiplicity of peaks in Fig. 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,[25] such as a bubble.[26] 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 were a clear pair of such resonances near 50 and 100 Hz).
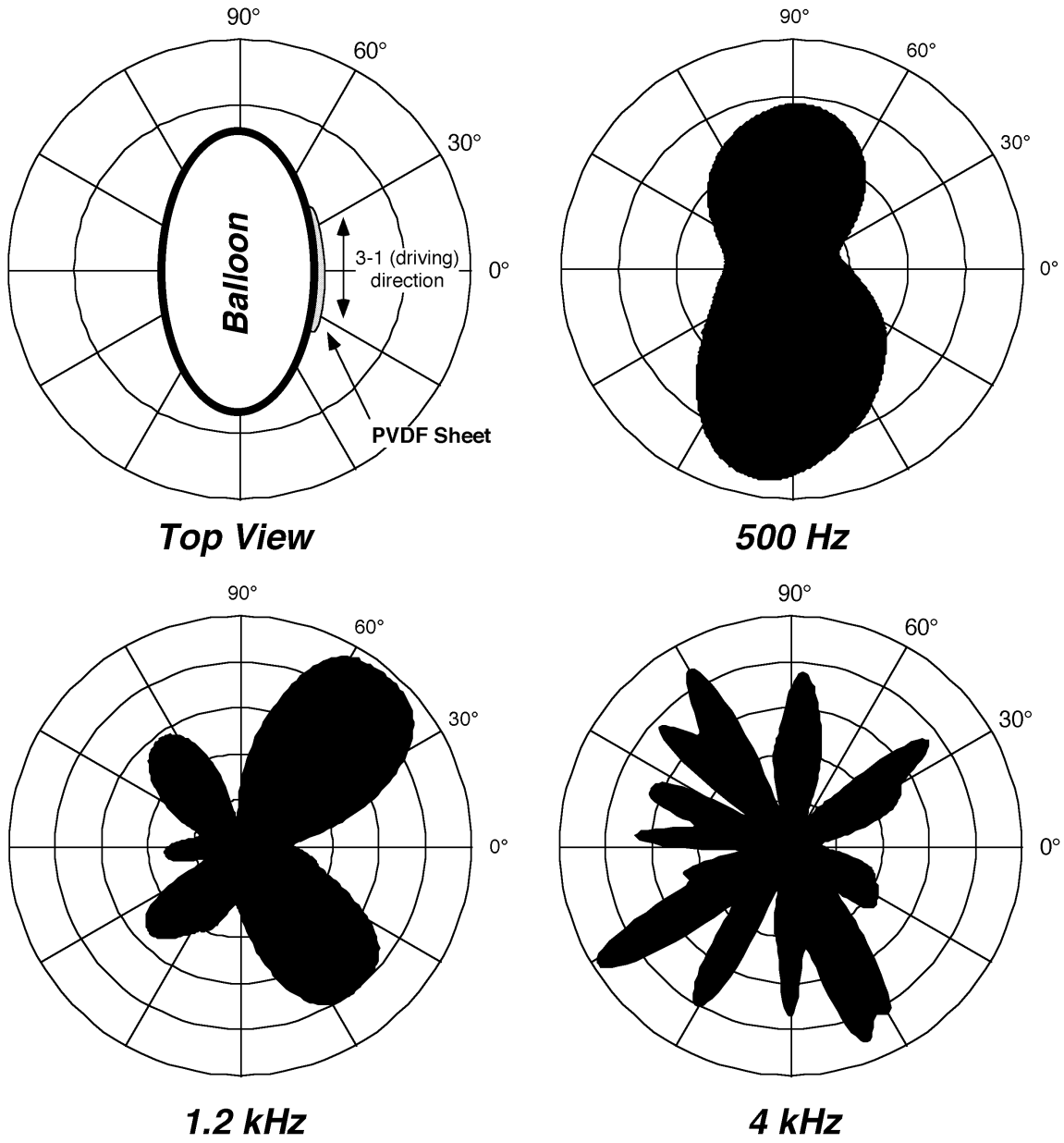
Figure 7: Horizontal, near-field intensity pattern of taut balloon measured at three frequencies

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 more complicated. Together with flexural modes being excited in the mylar membrane (such as seen in drumheads[27]), one would expect lots of peaks and nulls in the response, such as seen in Fig. 6.

Over the frequency range most relevant for reproducing speech (500 Hz - 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 discussed 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 below.

The PVDF sheet tested in Fig. 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 hanging 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. This data was collected by placing the microphone close (roughly 8") 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 RPM), while continually sampling the amplitude envelope detected at the microphone. Fig. 7 is plotted in polar coordinates; the drawing at upper left shows the angular reference. Although the display 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 this data is analyzed only for general trends.
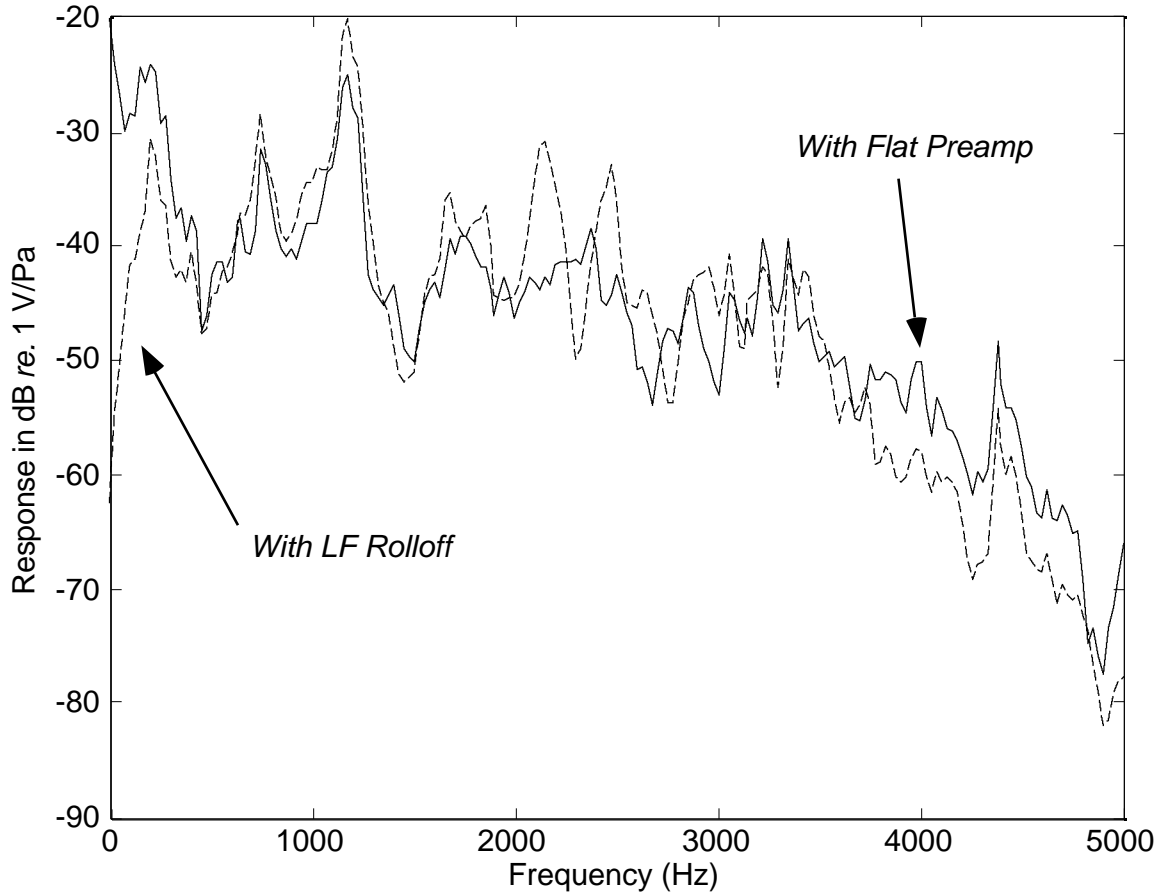
Figure 8: Sensitivity of balloon pickup with and without rolloff

At 500 Hz, the intensity pattern assumes a rough peanut shape, with the beginnings of a null forming near the center and maxima near ±90°. 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° 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°,180°) 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

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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 front-end of Fig. 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 Fig. 6, thus is well matched to the voice spectrum. These curves show the sensitivity of the balloon transducer in dB (*re.* 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.

6) Applications

Over sixty 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*, and another pair perpetually screamed "Cheeseburger" and "Pepsi" at one another. The largest installation was a cluster of 4 balloons, which were programmed with excerpts of Marvin Minsky reading from his "Society of Mind".[28] Until their batteries ran out, these 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[29] 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.

7) 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".

8) Acknowledgments

Biography

Joseph A. Paradiso received a B.S. in Electrical Engineering and Physics from Tufts University in 1977 and a Ph.D. in Physics at the Massachusetts Institute of Technology in 1981 as a C.T. Compton Fellow. From 1981-1983 he was at the Laboratory for High-Energy Physics at ETH in Zurich, where he developed precision particle trackers for the L3 experiment at the CERN laboratory in Geneva, Switzerland. During 1984-1994, he was at the Draper Laboratory in Cambridge, MA, where he conducted research in spacecraft control systems, image processing, sonar sensors, and

high-energy physics detectors for the Superconducting Supercollider. He was a visitor at ETH in 1991 and 1992 to develop fast pattern recognition systems for proposed detectors at the CERN Large Hadron Collider. He is also active in electronic music, and has designed several music synthesizers. Since 1994, he has been a research scientist at the MIT Media Laboratory, where his interests include the development of new sensors for human-computer interaction. He is currently the Technology Director for the Things That Think consortium.

References

1) Creme, L., Godley, K., "I Pity Inanimate Objects", from <u>Freeze Frame</u>, PD-1-6257, Polydor Records, 1979.

2) See: *http://ttt.www.media.mit.edu*

3) Kupferberg, L.C. and Tancrell, R.H., "Poly(Vinylidene Fluoride): Properties and Application in Acoustic Sensors", *U.S. Navy Journal of Underwater Acoustics*, Vol. 41, No. 1, January 1991, pp. 7-28.

4) Sessler, G.M., "Piezoelectricity in Polyvinylidenefluoride", *Journal of the Acoustical Society of America*, Vol.70, No.6, Dec. 1981, pp.1596-1668.

5) "Piezo Film Sensors Technical Manual", Document 65751, AMP Sensors Inc., Valley Forge, PA., December, 1993.

6) Kawai, H., "The Piezoelectricity of Poly (vinylidene Flouride)", *Japan J. Appl. Phys.*, Vol. 8, 1969, pp. 975-976.

7) Carlisle, B.H., "Piezoelectric Plastics Promise New Sensors", *Machine Design*, Vol. 58, No. 25, pp. 105-110, October 23, 1986.

8) Amato, I., "Fantastic Plastic", *Science News*, Vol. 136, No. 21, Nov. 18, 1989, pp. 328-329.

9) Klapholz, J., "Polymer Film for Transducers", *db Magazine*, November-December 1985, pp. 27-32.

10) Duperray, J. L., "Les Nouveaux Violons." *Diapason.* No. 296, July/August 1984, pp. 88-89.

11) Chan, H.L.W., Ramelan, A.H., Guy, I.L., Price, D.C., "VF$_2$/VF$_3$ Copolymer Line Hydrophone and Line Hydrophone Array for Ultrasonic Measurement", *Sensors and Materials*, Vol. 3, No. 1, 1991, pp 49-60.

12) Marschall, D.P., Pearce, R.E., Marschall, R.A., "Polar Seismic Surveying with Towed Hydrophone Array", *Sea Technology*, September 1994, p 45.

13) Clark, C.W., and Spikes, C.H., "Whales '95 Experiment Quicklook Briefing," Paper presented at the *Strategic Environmental Research and Development Review for*

Commander, Space and Naval Warfare Systems Command, Washington, D.C., December 1995.

14) Burke, S., Paradiso, J., Bailey, T., and Ciliberto, R., "Monopulse Piezopolymer Sonar Sensor", submitted to the *Journal of the Acoustical Society of America*, 1996.

15) Hughes, W.J., Allen, C.W., "A Shaped PVDF Hydrophone for Producing Low Sidelobe Beampatterns", *Proc. of the 1992 Symposium on Autonomous Underwater Vehicle Technology (AUV '92)*, IEEE Press, NY, 1992, pp. 219-223.

16) Burke, S. and Hubbard, J. Jr., "Distributed Transducers for Structural Measurement and Control", invited chapter appearing in Vol. 36 of Advances in Control and Dynamic Systems, C.T. Leondes, Ed., pp. 223-273 (1990).

17) Tom, E., "Polymer film arrays in pyroelectric applications", *Sensors*, Vol.11, No.9, Pt.1, Sept. 1994, pp.75-77.

18) Park, K.T., Radice, P.F., "Electroacoustic Novelties", US Patent No. 5,309,519, May 3, 1994.

19) Radice, P.F., "Air Buoyant Piezoelectric Polymeric Film Microphone" US Patent No. 4,843,275, June 27, 1989.

20) Flexible Film Products Group, Amp Incorporated, Valley Forge, PA.

21) Cremer, L., The Physics of the Violin, MIT Press, Cambridge, MA., 1984.

22) Paradiso, J.A., "Using the Interactive Piezo Balloon System", Internal memo PHM-95-1, Physics and Media Group, MIT Media Laboratory, October 5, 1995.

23) Cantrell, T., "Talking Chips", *Circuit Cellar INK*, The Compter Applications Journal, Issue #36, July, 1993, pp. 62-69.

24) Kitchin, C., Wurcer, S., "New Amplifiers Provide a Fully Packaged Solution for Sonar Applications", *Analog Briefings* (Analog Devices, Inc.), Vol. 7, No. 2, Summer, 1991, pp. 3-4.

25) Huang, J.C., "Harmonic Frequency Generation by a Pulsating Resonator Sonically Excited", *IEEE Transactions on Sonics and Ultrasonics*, Vol. SU-21, No. 2, April, 1974, pp. 106-114.

26) Kinsler, L.E., Frey, A.R., Coppens, A.B., Sanders, J.V., Fundamentals of Acoustics, Third Edition, John Wiley and Sons, New York, 1982.

27) Fletcher, N.H., Rossing, T.D., The Physics of Musical Instruments, Springer Verlag, New York, 1991.

28) Minsky, M., The Society of Mind", Simon & Schuster, Inc., NY, 1988.

29) Gerasimov, V., "Things that Talk", Master's Thesis, MIT Media Laboratory, February, 1995.

Below, I've included the users manual for the balloon circuit as an addendum.
This did not appear in the published ISJ paper.

Using the Interactive Piezo Balloon System

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This system consists of a 36" aluminized mylar balloon with shielded miniplug cord attached, plus an electronics card housed in a small box. The balloon cord is plugged into the drive electronics (through the hole on top of the box).

There is a sheet of PVDF (piezo foil) mounted on the balloon, behind one of the "10/10" stickers. This acts as both an acoustic pickup (vibration changes foil length, hence produces voltage across the foil) and speaker (voltage across the foil changes foil length, producing sound). Under standard operation, the electronics "listen" to the balloon for an auditory stimulus, and react by playing a stored sound through the piezo foil. An inflated balloon acts as a sounding board, producing appreciable volume and creating a sensitive (albeit resonant) microphone. The balloon should be inflated to be taut, otherwise its acoustic efficiency is quickly compromised. Helium canisters will be available in room 022 to replenish balloons that loose their fill. Ideally a mylar balloon will last several days before loosing significant gas, but there is a large spread in their longevity.

The balloons are tethered to their electronics boxes by their cords. In order to avoid strain on the valve (prematurely dumping gas), the cords should be tied off (with an inch or so of slack) onto the mylar tab that protrudes from the bottom of the balloons.

There is high voltage (several hundred volts) across the balloon foil when sounds are being played. Since the foil is insulated (and the current capacity is low), there is little need for excessive caution, but be a little careful when handling the circuit card with the power on to avoid mild shocks.

The balloon stores up to 20 seconds of audio, parceled into one, two or four separate messages. The sounds can be recorded using an onboard microphone, the balloon itself, or through an audio line-level source such as a CD player or tape deck. In the usual mode of operation, the balloon waits until it hears a significantly loud sound (the threshold is user adjustable). When the sound stops (drops below threshold), one of the recorded messages is played through the balloon. If the balloon is triggered shortly thereafter by another sound, it plays the next message, and so on, toggling through all stored sounds. In this fashion, one can have a "conversation" with the balloon; you talk to it and it replies with its stored messages. If the balloon is not triggered for a longer interval (circa 20 sec), it resets itself to reply with the first message. The electronics contain features to reject ambient crowd noise; the system can be made to respond to changes in the detected audio level, not its overall value. In addition to this "conversational" triggering mode, the balloons can be driven by an external audio source (thus used as a balloon speaker), or the messages can be directed to play through a simple digital interface, allowing them to be queued by other systems (such as the TTT badge stations). A balloon microphone output is also available, allowing another system access to the audio signals sensed by the balloon. The balloon volume is adjustable; a fully inflated device can get quite loud.

The figure on the following page shows the location of all the switches, connections, and features on the card. The function of each will be described below.
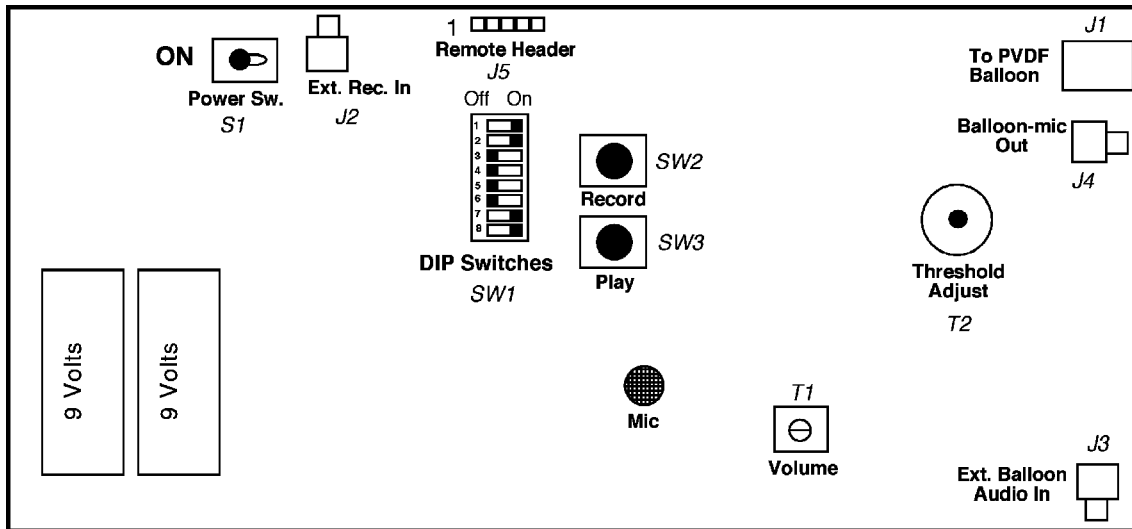
Adjustments, connections, switches, and significant features on the circuit card

Power

The circuit runs off two standard 9 Volt batteries. The power drain is fairly low when the device is not producing sound; it should be able to run for several days if it isn't frequently playing. Nonetheless, I've been able to run the system for over 5 hours without major battery rundown when continually making noise. Regardless, at least until after 10/10, I'd recommend keeping the units off when not being used (or pop fresh batteries in just before the 10/10 visits start). Loss of power will not affect the stored sounds; they are written in a nonvolatile switched capacitor array inside the ISD chip, and decay very slowly (i.e. months, years...). The power switch is a simple toggle, on when it is thrown toward the left side of the board (near the batteries).

Adjustments

The balloon volume is adjusted by trimpot T1. Adjust this so the audio played on the balloon is sufficiently loud but not distorted. This control affects the volume of both internally stored sounds and external audio input from J3.

The threshold control (T2; the blue potentiometer) should be adjusted to produce the desired triggering sensitivity. Clockwise makes the device more sensitive; full counterclockwise prevents acoustic triggering. The setting of this adjustment has crucial affect on the behavior of the balloon. For most applications, a setting of 1/4 to 3/4 full is adequate. If the balloon triggers too frequently, this can be cut back. If it triggers too early (i.e. it doesn't wait until a speaker is silent when in conversational mode), this adjustment should be increased. The balloons are very sensitive. If one desires the system to be minimally responsive (i.e. you have to hit the balloon or yell at it to get a trigger), this pot should be nearly turned full off. Some practice with this adjustment is needed to get a feel for its effect. In some cases, the balloons may appear insensitive with the threshold up near its max; here the circuit is waiting for the sound dynamics to die away before triggering, hence the adjustment should be backed off. The threshold may need tweaking after a room is full of noisy people (and/or other balloons).

DIP Switches

The mode of operation is set by the DIP switches (SW1). The 4-message default setup is shown in the figure (the black squares indicate the switch position; right is

generally on, as labeled on the switch). If the switches are set in this manner (S1,S2,S7,S8 on, S3-S6 off) the balloon is record-enabled, records off the card-mounted microphone, compensates for ambient background sound, waits until a sound finishes before triggering, and will record/play 4 cycling messages. This is probably sufficient for most applications. Other modes can be selected, however, in order to better configure the system for certain applications. The functions of these switches are summarized on the card (above the batteries), and are detailed below:

S1 (top) is the record enable. If this is off, messages can not be recorded (the record button has no effect), thus a set of optimal messages can be protected against accidental erasure. S1 must be on for recording.

When S2 is on and S3 is off, the card-mounted microphone is used for recording. When S2 is off and S3 is on, the signals coming from the balloon are used for recording. The sound quality from the card-mounted mic is generally superior (plus it is processed through the on-chip AGC), thus it is the preferred default. Acceptable sounds can be recorded from the balloon as well (they have a different character); bear in mind that these aren't processed through the AGC, thus more attention should be paid to acoustic levels.

If S2 and S3 are off, line-level audio from the external input (J2) are recorded, as described below.

If S4 is off, the balloon responds to relative changes in sound level; if S4 is on, the balloon triggers on absolute sound level. This switch has an important effect on balloon operation. The balloon system arms itself when detecting a sound above threshold; the sound is not played until the detected audio drops back below threshold for an appreciable interval (i.e. quarter to half second). This allows the balloon to engage people in mock conversations; it usually waits for them to finish talking. In an environment with lots of ambient noise, however, the balloon will immediately arm itself, but will not play the sound, since the noise never drops below threshold. The S4 option was installed to avoid this problem. With S4 off, the balloon trigger normalizes to the ambient sound level, and responds to changes; i.e. one can yell above the din to the balloon and it will reply. Whether to run with S4 on or off depends on the anticipated environment. The balloons will be less "aggressive" with S4 on, but the threshold will need careful adjustment to prevent their triggering function from being inhibited in a steadily noisy location.

S5 determines whether the balloon will trigger on the attack of a sound above threshold, or wait until the sound again drops below threshold before triggering. With S5 on, the balloon triggers promptly, immediately playing back when it hears an input above threshold. With S5 off, the balloon waits until the sound again drops below threshold before playing its message, as described above. S4 and S5 work together; i.e. the balloon can be made to trigger on the attack of a significant change in the detected sound, etc.

S6-S8 select the number of messages that are recorded and played. With all three switches off, only one message (up to 20 seconds in duration) is stored. With S6 on and S7,S8 off, the balloon stores two messages (the first up to 8 seconds and the second up to 12 seconds). With S6 off and S7,S8 on, the balloon stores four messages (the first three up to 4 seconds and the last up to 8 seconds).

Record/Playback

Pushbutton SW3 causes the current message to play back over the balloon. By repeatedly pressing SW3, all messages can be auditioned and the balloon playback can be checked.

Switch SW2 allows sounds to be recorded onto the ISD chip. In order to properly setup for recording, turn the threshold (T2) all the way down, make sure that the record enable (DIP switch S1) is on and check that the appropriate audio source is selected with S2 and S3 as described above.

The record button (SW2) must be held down for the duration of the recording. No protection is provided for overflowing into the next message in the sequence, thus SW2

must not be depressed any longer than the maximum time allotted for a particular message (otherwise the next message is destroyed). The number of recorded messages is set by DIP switches S6-S8, as described earlier. Recapping their durations:

One message selected: 20 seconds available
Two messages selected: First is up to 8 seconds, second is up to 12 seconds
Four messages selected: First 3 are up to 4 seconds, last is up to 8 seconds

If the system is left alone without playing back for at least 20 seconds, the address counter is reset and the first message is selected, hence may be recorded. After recording, the play button must be pressed to advance to the next message location (the audio just recorded is played, and the address is incremented to point to the next message). Wait at least one second before hitting the play button after recording, to insure proper resetting. By advancing through messages with the play button, any message can be selected to be overwritten. Remember that the message to be recorded is the one that comes *after* the message that has just been played. Also remember that a message must be recorded within roughly 20 seconds of the last message playback, otherwise the address counter is reset and the device again points to the first message.

As an example, suppose you want to record a message from the on-card microphone. Make sure that dipswitches S1 and S2 are on, S3 off. Repeatedly hit play (don't hold it down) until the system has played the message located before the one desired to be overwritten. Move 8-12" or so away from the mic (labeled in the board diagram). Push the record button and immediately start talking. Hold record down until you have finished speaking, then promptly release it (make sure that you do not hold it down any longer than allocated; see the list of maximum recording times above). After waiting a second or so, hit play to hear the message that you've recorded. If you want to record the next message in the sequence, you can immediately press record again, and repeat the process. If you'd like to re-record your message, press play to cycle through to the message immediately before, then repeat the record procedure.

If the dipswitches are set for only one 20 second message, the same message is always recorded or played back; there is obviously no need to "cycle through" as above.

The above procedures also apply when recording off the balloon or an external audio source. As these inputs don't use the on-chip AGC (automatic gain control), some experimentation with loudness or levels may be needed to produce the best recording clarity.

Connectors

The balloon is plugged into the mini-phonejack J1. Although the connector is the same, please do not plug your walkman headphones, etc. in here; the circuit expects a much higher impedance, and the voltages are considerable.

None of the other connectors need to be used for the simple "talking balloon" applications, but they provide a few options to interested hackers, thus their functions are detailed below.

Line-level audio (i.e. from a stereo component or PC) can be applied directly to the balloon through RCA jack J3. When driving the balloon externally in this fashion, the threshold (T2) should be turned full off (counterclockwise), otherwise the balloon will start playing its own stored sounds as well. Trimmer T1 likewise controls the volume of the external audio applied to the balloon.

The audio picked up by the balloon is available at RCA jack J4. This is a line-level output. Be aware, however, that a huge signal is present here when the balloon produces sound. Not enough to damage a mixer, etc., but sufficient to pin levels and potentially damage speakers or hearing. The balloon mic has a resonant sound (like having one's head

in a balloon, logically enough); on-card filters compensate this somewhat by rolling off the low end, but the effect is still present.

A line-level audio signal can be applied to the External Record Input (J2) to enable direct recording of audio from an external source. The record microphone inputs should be switched off on the DIP switches (SW1; switches 2 & 3) when this input is used, as described above. This input is not treated by the on-chip AGC, thus the levels should be appropriately adjusted to be loud enough but not distorted. In some cases, the use of an external compressor may help to improve signal-to-noise.

The header J5 provides a simple digital interface to directly select and play messages. The pinout is as follows:

Remote Header (J5) Pinout

Pin 1: Ground
Pin 2: Trigger input
Pin 3: +5 Volts
Pin 4: A0 Input
Pin 5: A1 Input

A pulldown to ground on pin 2 will cause the currently addressed sound to play back. The width of this pulse should be at least 10 milliseconds to insure proper latching. Pins 4 and 5 are TTL-level inputs that allow a stored message to be directly addressed. These pins are active-high. To be safe, setup the address on these pins at least 10 milliseconds before the trigger pulse arrives, and keep them steady through the trigger duration (this is probably conservative). When addressing specific messages, DIP switches S6,S7,S8 should be all set off, otherwise the internal message counter will contest the external addresses. The five volt supply is available at pin 3 to power external peripherals (keep the current low; it comes off a 78L05 regulator).

Acknowledgments