Imaging Around Corners With Ultrasound

Biyeun M. Buczyk*
MIT, Dept. of Physics

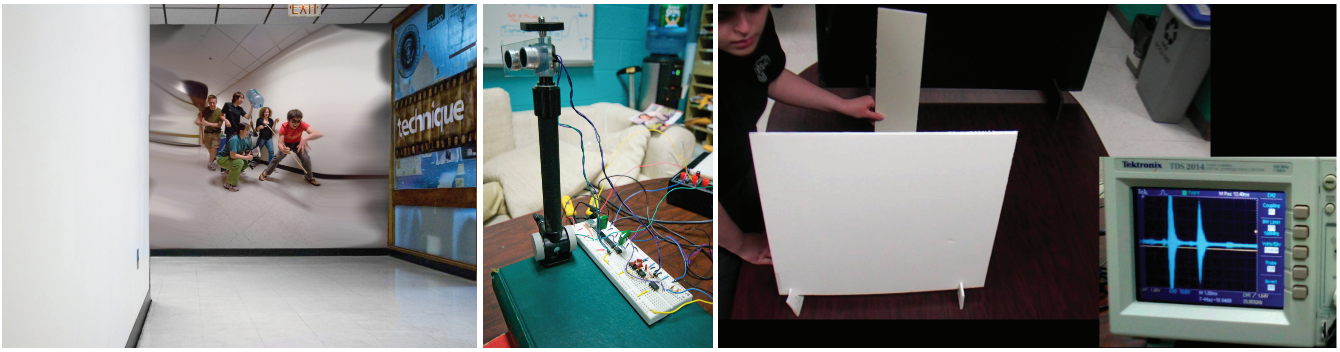

Figure 1: *Left: Turning a wall into a "mirror" by using multi bounce reflections to look around the corner. Middle: The prototype ultrasonic device for looking around corners. Right: Carrying out the experiment and finding a third bounce.*

Abstract

We provide a proof of concept for imaging around corners using ultrasound, expanding on methods presented by Kirmani et al. [2009], which permit a multi-path analysis of sound to recreate the 3D geometry—both visible and hidden parts—of a scene while remaining both eye and body safe. The limitations and advantages of ultrasound imaging in comparison to femtosecond transient imaging are explored. We then propose approaches for improving our proof of concept ultrasound device and discuss the benefits of combining the two transient imaging methods for real world applications.

1 Introduction

Sound is widely used in range finding and non-invasive medical imaging applications, such as SONAR, diagnostic and obstetric sonography. However, all of these methods rely solely on information obtained from first-received echos, limiting even the most advanced 3D ultrasonography algorithms from detecting obscured or hidden geometries.

This paper demonstrates the possibility of using multi-bounce echos to obtain hidden 3D geometries with the simple setup of a transmitting and receiving ultrasound transducer pair. Using the multi-bounce echo information from this setup, we propose a method based on the *Transient Light Transport* framework created by Kirmani et al. for reconstructing scene geometries.

1.1 Related Work

Transient Light Transport: Proposed by Kirmani et al., *Transient Light Transport* describes the behavior of light during scene illumination. A first bounce of light is produced by incident illumination on a patch p_1, which then produces a set of inter-reflections. While the behavior of these inter-reflections is dependent largely on material properties, Transient Light Transport assumes Lambertian surfaces for simplicity. As a result, incident light reflects in every direction with equal intensity, resulting in some of the first bounce landing on the sensor, and some landing on other patches. The first bounce incidence on these patches produces a second bounce—in Figure 2 we see second bounces from p_2 and p_3. If the patch is visible to the camera, the second bounce reaches the sensor. If the patch is not visible to the camera, no second bounce reaches the sensor, as is the case with the occluded patch p_2. The second bounce further goes on to produce third bounces off other patches in the scene. In this case, the second bounce from the occluded patch p_2 produces a third bounce off p_1 which reaches the sensor. These third bounces off of hidden objects are what allow for imaging around the corner.

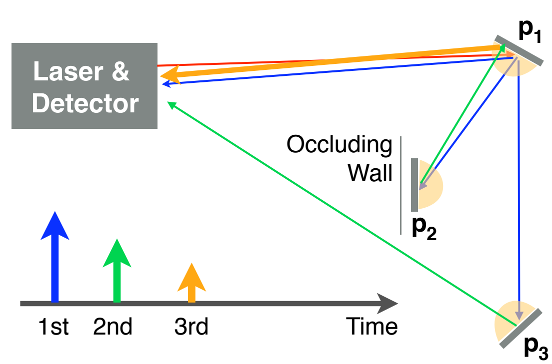

Figure 2: *A very simplified diagram of the Transient Light Transport geometries for Femtosecond Transient Imaging.*

Femtosecond Transient Imaging: Traditional light based imaging integrates the luminous intensity value at each point after light has reached an equilibrium in global illumination to produce a 2D image. This equilibrium occurs when light has reached steady state and has traveled over all possible paths during the exposure time. Femtosecond Transient Imaging [Kirmani et al. 2009] uses

*e-mail: biyeun@mit.edu

the transient property of light to observe how light travels through a scene during the first few nanoseconds of illumination before it has reached steady state. A 3D time image $I(x, y, t)$ is generated using pulsed femtosecond laser illumination and a high speed camera to record the intensity of patch p_i at (x_i, y_i) over time. The direction of the impulse ray (θ_i, ϕ_i) is varied to illuminate all scene patches $i = 1, ..., M$, creating a 5D Space Time Impulse Response of the scene $\mathcal{S}$, **STIR($\mathcal{S}$)**.

3D Ultrasonography: 3D ultrasound, developed by [von Ramm and Smith 1987], produces a 2D image of a 3D object with perspective capabilities. The image is created by steering 2D phased array of piezoelectric transducers over a range of different azimuth and elevation angles (θ, ϕ). A 2D slice of the 3D object is obtained for each direction. The intensity values for each point in this 2D slice represent the integrated ultrasound echoes at each receive path. These images are merged into a 3D depth image of the object.

2 Applying Transient Light Transport to Ultrasound

Due to physical differences between light and sound, the behavior of each phenomena differs greatly during scene illumination. Consequently, the method of Transient Light Transport will require significant modification when applied to ultrasound.

The primary assumption of Transient Light Transport is that surfaces are Lambertian or, at the very least, mostly diffuse. This assumption can be made as most surfaces (walls, tables, etc.) are rough on the order of a few hundred nanometers—the wavelength of light. However, this is not necessarily the case for sound, which travels at a much slower speed than light, exists at lower frequencies, and has a longer wavelength. The longer wavelength results in mostly specular interactions since these surfaces, appearing rough to light, appear smooth to sound.

In natural settings—trees, rough cliffs, pebbles, etc.—sound can be approximated as diffuse, since the surfaces of these natural objects are rough on the order of cm to mm, the typical wavelengths of ultrasound. This setting can use inverse geometric methods for Transient Light Transport described by Kirmani et al.

The largely specular behavior of sound around manmade materials results in easier geometric computations. For instance, it is difficult to determine the angle of incident light under a Lambertian assumption. A problem arises when two hidden first bounce incident patches are placed equidistantly from a first bounce source patch and result in final third bounces with equal time of flight data. This scenario is avoided with mostly specular surfaces since the direction of the most intense reflection is dependent on the incident angle. The initial pulse direction (θ_i, ϕ_i) will only produce bounces received by the sensor for specific combinations of (θ_i, ϕ_i), assuming a perfectly coherent incident pulse. Each (θ_i, ϕ_i) that results in a detected bounce (whether first, second or third) will uniquely correspond to a patch whose location is easily computed using euclidean geometry with time of flight information and the law of reflection.

While a mostly one-to-one correspondence between (θ_i, ϕ_i) and patch is computationally easy for detecting the presence of objects around a corner, it becomes difficult to image that object. With Transient Light Transport, it is assumed that all patches capable of receiving first bounce reflections should produce a detectable third bounce. This is not the case with sound, since many of the patches will produce bounces that are unlikely to ever be directed back to the sensor, as shown in Figure 3.

For each of these imaging cases, we assume a mostly coherent, directional sound source. However, producing coherent, directional sound waves similar to lasers is difficult to approach, let alone attain.

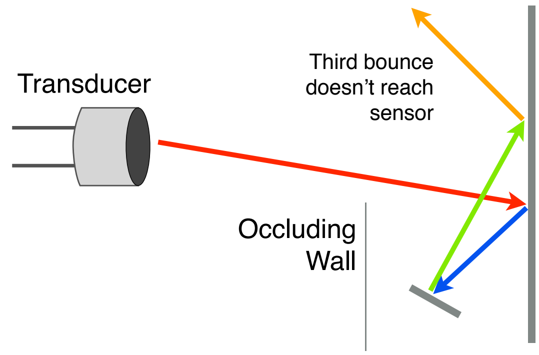

Figure 3: *An example of ultrasound coming in at a particular angle that scatters the third bounce away from the transducer.*

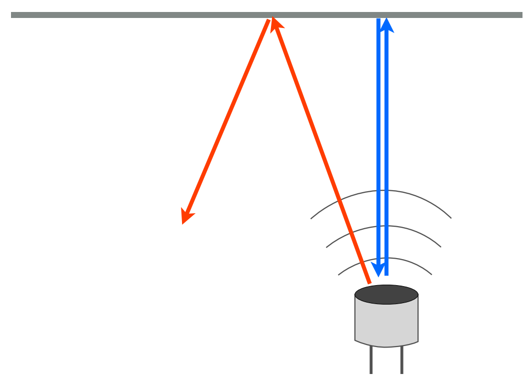

Figure 4: *A diagram showing the problem of generating too many spurious reflections from a wide beamwidth.*

3 Controlling the Beamwidth and Direction of Sound

In order to identify the origin of each specular reflection, the angle of the incident beam must be known. Unfortunately, single ultrasonic transducers often produce a beamwidth that is too wide for producing unique reflections at each (θ_i, ϕ_i), illustrated in Figure 4. Several methods can be employed to control beamwidth, but encounter limitations when trying to produce ultrasound beams in air.

3.1 Varying Transducer Diameter

A simple approach for controlling beamwidth, θ_{BW}, is to modify the diameter of the transducer. Transducers with a smaller diameters will produce more highly divergent beamwidths compared to larger diameter transducers. However, this method comes at the cost of angular resolution. While a large diameter transducer will produce a highly directional beam, it will not be able to resolve objects smaller than $2D \sin\left(\frac{1}{2}\theta_{BW}\right)$, where D is the distance between the source and the object.

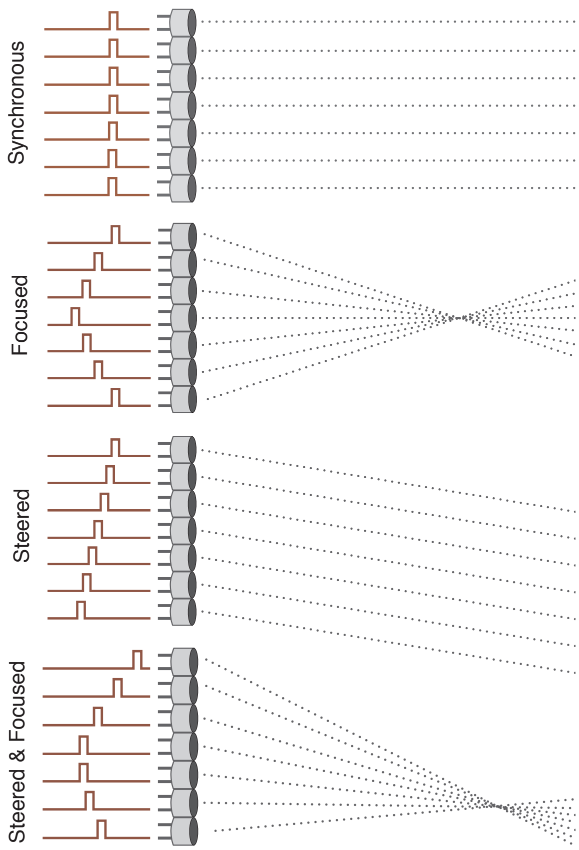

Figure 5: *The different methods for beamforming using a phased linear array.*

3.2 Phased Arrays for Beamforming

Phased arrays provide another method for beamforming. By placing several transducers in a row and controlling the phase of the output of each transducer, the sound can be made more directional, steered, or focused, as described in Figure 5. While this seems like an excellent solution, commercially available single ultrasound transducers are enclosed in a casing that renders it impossible to satisfy the Nyquist theorem when placing the transducers side by side to form the array, as illustrated in Figure 6. If the Nyquist theorem is not satisfied, grating lobes will become too pronounced and create produce spurious "ghost images" on the resulting signal.

3.3 Frequency and Acoustic Impedance

An instinctive method would be to increase the frequency of the source, since higher frequencies result in smaller beamwidths. However, due to the high acoustic impedance mismatch between air and sound, higher frequencies are prone to greater atmospheric absorption. The amount of atmospheric absorption for each frequency, shown in Figure 7, taken from [Bass et al. 1990], is dependent atmospheric pressure, humidity, and temperature. For example, in a room at 20°C, 50% humidity, and 1 atm, 40 kHz would be absorbed at 1.32 dB/m and 1 MHz at 163.82 dB/m.

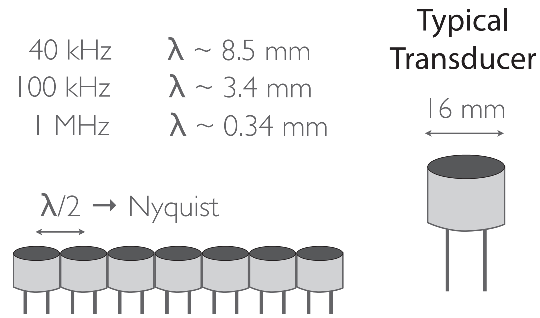

Figure 6: *The Nyquist Theorem is satisfied when the distance between the centers of all the sources is equal to half the wavelength. Unfortunately, many commercially available transducers at 40 kHz are nearly twice the 8.5 mm wavelength.*

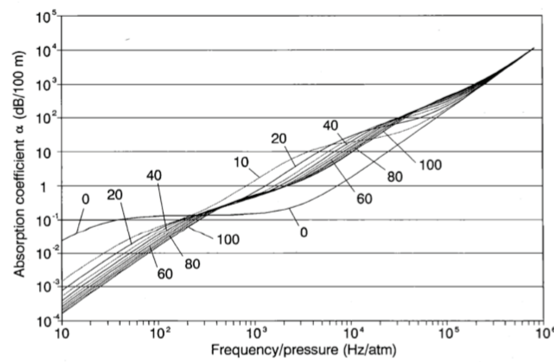

Figure 7: *The relation between frequency and acoustic absorption.*

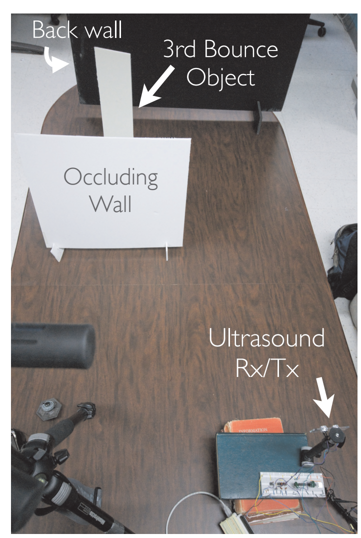

Figure 8: *A photograph of the experimental setup.*

4 Hardware Prototype

This high impedance mismatch is not the case for water, which is far more effective medium for transmitting sound. In addition to a lower impedance mismatch, sound travels faster in water, resulting in longer wavelengths than air. For instance, 40 kHz produces a wavelength of roughly 8.5 mm in air, while in water it is approximately 3.7 cm. These longer wavelengths make it easier to satisfy the Nyquist Theorem since the larger, more readily available transducers will be able to fit together enough to satisfy the sampling area.

We create an ultrasonic transmitter and receiver prototype using two US 1640 40 kHz piezoelectric ultrasound transducers with beamwidths of 50 degrees to obtain multi bounce data. The transmitter is driven by a PIC micro controller outputting 4 cycles of a 40 kHz square wave every 100 ms. This square wave is amplified using a push-pull driver to drive the transducer at a high peak to peak voltage (16 V to 30 V) yielding an intensity great enough to yield multi bounce data. The receiving signal is amplified 100 times, fed through an op amp peak detector, and outputted to a National Instruments USB-6009 data acquisition (DAQ) device operating at 24 kS/s. The DAQ converts the analog signal to a digital signal that is read by a computer.

5 Obtaining Third Bounce Data

5.1 Experimental Setup

The initial experiment for obtaining ultrasound multi bounce information is a simple setup of three foam core "walls." A large wall is placed at the back to catch first bounces. Roughly two feet in front of it, a wall half its size—the occluding wall—is positioned on the left side of the table. A thinner four inch wide wall is placed between the two large walls, hidden from direct view of the ultrasound transducers. This smaller wall is rotated at a 45 degree angle from the back wall to adequately reflect the ultrasound first bounce. Figure 8 shows a photograph of the setup.

5.2 Demonstration and Performance Evaluation

A video clip of small wall movement and the corresponding changes in bounce data is available as supplementary material. Figure 9 shows three screen captures, the first with the small wall in its starting position, the second with the small wall turned slightly to reflect less of the third bounce, and a final showing the result without a hidden wall.

An example of data obtained from the setup described in Section 5.1 is shown in Figure 10. The first large peak is the result of the wide beam of the signal getting picked up by the receiver. The second large peak is the first bounce off the back wall, and the third large peak is the third bounce off of the hidden objects. The time between pulses reveals the relative distances of the objects.

Ultrasound reflecting off object around the corner behaves as expected. Due to the highly specular nature of ultrasound under these material conditions, the resulting third bounce signal is extremely sensitive to the rotation angle of small wall plane. No third bounce signal is obtained outside a 30 and 60 degree rotation from the back wall. The wide beamwidth is also noticeable, since a portion of the first bounce off the occluding wall appears is in the received signal, labeled in Figure 10. Lastly, the fact that the third bounce signal is almost the same intensity as the first bounce suggests specular reflection off the walls, since diffuse reflection would have produced a very small third bounce signal, as seen in Kirmani et al.

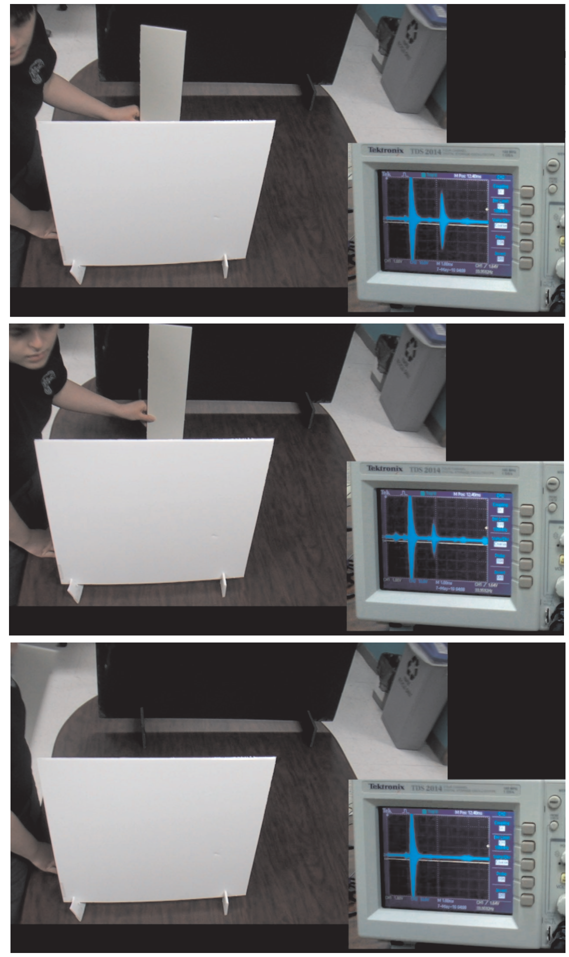

Figure 9: *(Top) Hidden object angled at maximum intensity. (Middle) Hidden object angled away to reduce intensity. (Bottom) Hidden object removed—no third bounce.*

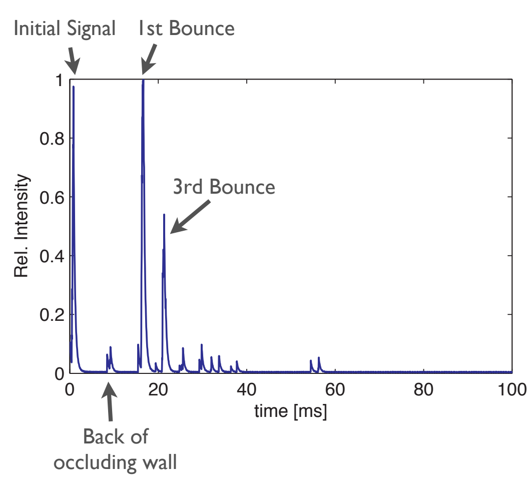

Figure 10: *An example of the raw multi bounce data.*

6 Future Directions

6.1 Underwater Ultrasonic Imaging Around Corners

Since the first experiments in air have sufficiently shown a proof of concept for ultrasonic imaging around corners, further experiments must be made underwater due to the acoustic advantages described in Section 3.3 that water provides over air. The primary reason why this is not the first proof of concept experiment is due to the higher cost of waterproof transducers and a water retaining tank for the imaging scene.

6.2 Circular Piezoelectric Stack for Air Ultrasound

While ultrasound is primed to work underwater, more experiments should also be done to improve the imaging performance in air, as ultrasound still boasts many useful advantages over femtosecond transient imaging with high powered lasers. Since single commercially produced ultrasonic transducers have already proved too large to install in arrays, a piezoelectric stack of tiny ultrasonic transducers will provide the best approach for conducting further in-air experiments. An ideal stack contains circular components which allow the beam to be focused at a point and not a line, which is the case for a 2D phased array.

6.3 Combining Ultrasound with Femtosecond Transient Imaging

While ultrasonic imaging in a specular environment boasts significant advantages for understanding and pinpointing geometries of objects in a scene, femtosecond transient imaging still provides a cleaner method for imaging these objects due to the more diffuse behavior of light. An ideal around the corner imaging device for real world applications should take advantage of both technologies and combine the unique information obtained by each phenomena to create a better image of the scene.

6.4 High Speed 3D Imaging

Outside from obvious military, civilian, research, and medical applications—such as detection of enemy combatants around corners, accident prevention at high-risk road intersections, automated robotic navigation, or less invasive diagnostic ultrasonography in tight regions—transient imaging might eventually provide users with a device that can recreate the entire 3D geometry of a scene, including hidden objects. Due to the speed at which these phenomena operate, especially light, transient imaging also provides a way to capture high speed 3D data. The latter, however, will require improvements in high speed cameras to work reliably in real world applications.

7 Conclusion

We have demonstrated a proof of concept device for ultrasonic imaging around corners, building upon the work done by Kirmani et al. Additionally, we have shown the differences in behavior between sound and light when it comes to real world imaging around corners and discussed the advantages and limitations of our method in comparison to Kirmani et al. The proof of concept device and discussion have been the primary contributions of this paper. We hope this paper can provides an adequate summary of the knowledge gained by performing this first ultrasound experiment and will inspire others to make improvements in equipment and experiment with different scenarios for imaging around corners.

8 Supplementary Materials

`http://stuff.mit.edu/afs/sipb/user/biyeun/Public/fi/`

Acknowledgements

We thank Quentin Smith (MIT) for providing several electronics components and the data acquisition device. We also thank Tyler Hutchison and Andreas Velten for sharing their infinite wisdomry. The MIT Student Information Processing Board (SIPB) was instrumental in providing an amazing oscilloscope, and many thanks to The Tech for allowing the use of their office space for several experiments. Lastly, thank you to the Technique managing board for taking time out to pose for the camera.

References

BASS, H. E., SUTHERLAND, L. C., AND ZUCKERWAR, A. J. 1990. Atmospheric absorption of sound. *Acoustical Society of America 88*, SSN 0001-4966 (Oct.), 2019–2021.

KIRMANI, A., HUTCHISON, T., DAVIS, J., AND RASKAR, R. 2009. Looking around the corner using transient imaging. In *Proceedings from CVPR 2009*, CVPR.

VON RAMM, O., AND SMITH, S. 1987. Three-dimensional imaging system. *United States Patent*, 4 694 434 (September).