Feasibility Study of DTMF Communications for Robots

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Abstract

This technical report summarizes a year-long undergraduate research project by the first author. As the development of individual and cooperating autonomous robots advances, the need for a robust and reliable communication method becomes apparent. This paper summarizes a study conducted to examine the feasibility of implementing Dual-Tone, Multi-Frequency (DTMF) as an alternative mean of communication to Radio Frequency (RF). With advantages of simplicity and audibility, the hypothesis is that DTMF could replace RF in simple communications between robots or robots and devices. The conclusion is that acoustic communication in general not recommended for mobile robot applications due to the unreliability in acoustical integrity of the signal during transmission. This paper proposes other application areas, such as hospital/home healthcare environments and large networks with static nodes, where DTMF is feasible and would be advantageous over RF.

I. Introduction

Being able to achieve reliable communication is an important open area of research to robotics as well as other technology areas. As interest in robotics continues to grow, robots are increasingly being integrated into everyday life. The results of this integration are end-users possessing less and less technical knowledge of the technology. For example, consider the application of mobile robots in the health care industry, where the intended end users are patients themselves. In this case, the need for simplified, reliable, and user-friendly robot designs is of utmost importance.

Currently, the primary mode for robot communication uses RF (radio frequency). RF is an obvious choice for communication since it allows more information to be transferred at high speed and over long distance. However, the use of RF contributes to enhancing the already mysterious nature of robotic technology. This paper explores the use of acoustic communication as a mean

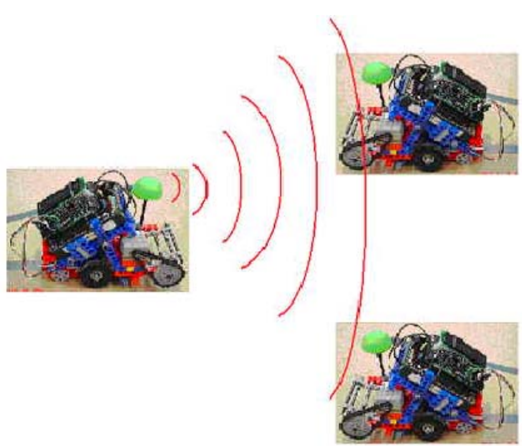

Figure 1. Overall goal of robots' ability to communicating acoustically: broadcast, multi-cast, uni-cast, or two-way communication.

to send/receive simple instructions for robots in applications where the end users lack technical specialty. Acoustic communication is a novel idea where the users are allowed to "listen in" and monitor the existence of communication to a certain level. This technique also reduces reliance on RF and, in some sense, makes the robot less intimidating.

To implement acoustic communication, dual-tone multi-frequency (DTMF) technology is used. DTMF has been in existence and used by the telephone systems for many years. Implementing an existing scheme that has proven to work reduces the hassle of defining new standards and allows the system to be compatible later on. Furthermore, such simple algorithm as DTMF allow for acoustic communication without the need of complicated voice recognition software.

The overall goal of the project is to investigate whether it is feasible to have robots communicate with each other acoustically using DTMF technology efficiently, as shown in Figure 1. Long-term objectives of the research project include the following:

- Investigate the feasibility and efficiency of implementing DTMF as a method of communication.
- Advance capability of robotics technology in health care and in homes.
- Produce an alternative method to RF communication and reduces the amount of RF noise in the environment.
- Decrease the mystery of robots for the average user.

This paper describes a feasibility study that was conducted to implement DTMF communication between two robots. The paper is organized as follows: Section II describes the project implementation; Section III reports the experimental results; and Section IV concludes the paper and states future work.

II. DTMF Communication and Experimental Setup

Dual-Tone Multi-Frequency (DTMF) is perhaps the most widely known method of Multi Frequency Shift Keying (MSFK) data transmission technique. DTMF was developed by Bell Labs to be used in the telephone system. Most telephones today uses DTMF dialing (or "tone" dialing). The DTMF standards define the overlaying of two pure sinusoidal waves by additive combination.

$$x(t) = A\cos(\varpi_l t) + B\cos(\varpi_h t + \phi) \qquad (1)$$

Where ϖ_l and ϖ_h are the low and high frequencies of the sine waves being used, A and B are the amplitude of the signals and ϕ is the initial phase shifts.

	1209 Hz	1336 Hz	1477 Hz	1633 Hz
697 Hz	1	2	3	A
770 Hz	4	5	6	B
852 Hz	7	8	9	C
941 Hz	*	0	#	D

Table 1. DTMF signal frequency encoding table.

The DTMF technique outputs distinct representation of 16 common alphanumeric characters (0-9, A-D, *, #) on the telephone. The lowest frequency used is 697Hz and the highest frequency used is 1633Hz, as shown in Table 1.

Remark: Acoustical transmission (using actual sound) is not a commonly implemented method of DTMF signal transmission. A distinction should be made that DTMF is an encoding scheme for data transmission, not a method. However, the important key

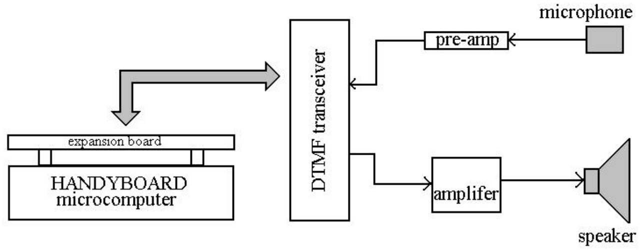

Figure 2. Hardware block diagram of the DTMF transceiver interfacing to the Handyboard.

here is recognizing that the DTMF frequency range falls within the audible range, hence can be transmitted acoustically using sound wave.

The Handyboard controller is used as the platform for the experimental implementation. The Handyboard is a microcomputer with a 68HC11 microprocessor [6]. Though the Handyboard's features and capabilities are limited, it is sufficient to handle DTMF communication (which further reiterates its simplicity without need for complicated technology). The robots' frames are made of LEGOs and are capable of basic mobile functionality. The task is to have one robot send an instruction to another using a speaker. The receiving robot will decode the message and response accordingly. Figure 2 shows the block diagram of the DTMF hardware for each robot.

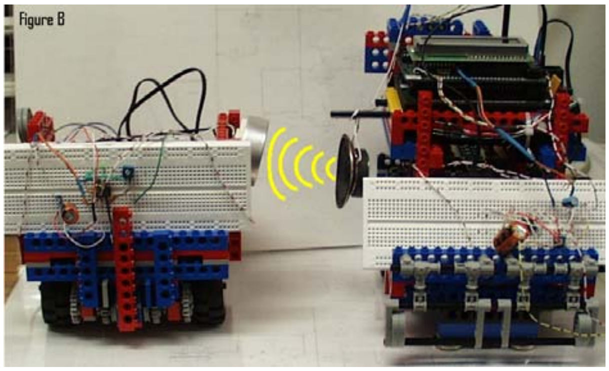

Figure 3. (B) Robots with DTMF capability

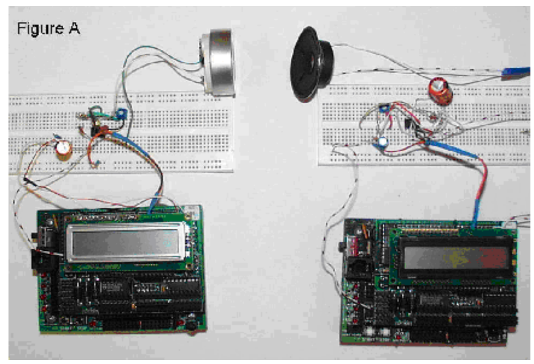

Figure 3. (A) DTMF hardware on the Handyboard.

The Clare™ 8088 – a commercially available DTMF transceiver chip – is used to generate the signal. The signal is then amplified for audible output via a small 8-ohm speaker. On the receiving side, a condenser microphone is used to pick up the signal. The signal is then deciphered and acknowledge by the receiver robot. The receiver robot then takes the appropriate action as commanded by the sender to prove successful transmission. Figure 3A shows the DTMF hardware on the Handyboard controller, Figure 3B shows the robot setup with DTMF capability.

Remark: There is an issue arose during implementation of the hardware that requires attention. Most of small-scale mobile robots use battery packs that have limited power output capability. This limitation of the robot's onboard power supply sets a limit on the maximum power delivered to the speaker and consequently its effective range. For the implementation of this experiment, the author is satisfied that the current amplification is sufficient for the robots' current small test environment.

The experimental setup includes two robots in a 4 by 6 foot table with obstacles including sand traps and trees. The goal is for the robots to send and receive information to one another as they navigate the environment. The experimental setup is represented in Figure 4.

III. Experimental Results

The experimental testing of DTMF communication is designed to carry out in three stages. The first stage is testing the output of

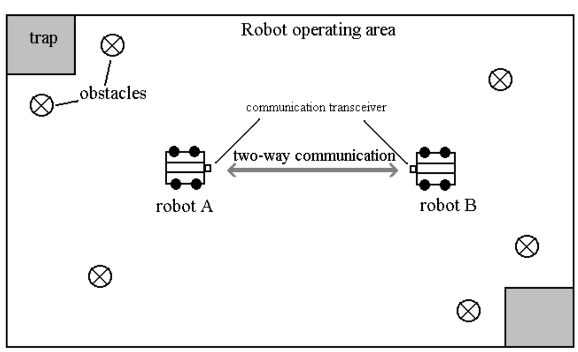

Figure 4. Robot testing environment with obstacles (sand traps and trees).

the hardware in comparison with computer simulation. The second stage is attempting data transmission while robots are immobile (stationary communication nodes). The third stage is when the robots attempt to navigate the environment (Figure 4) while communicating using DTMF.

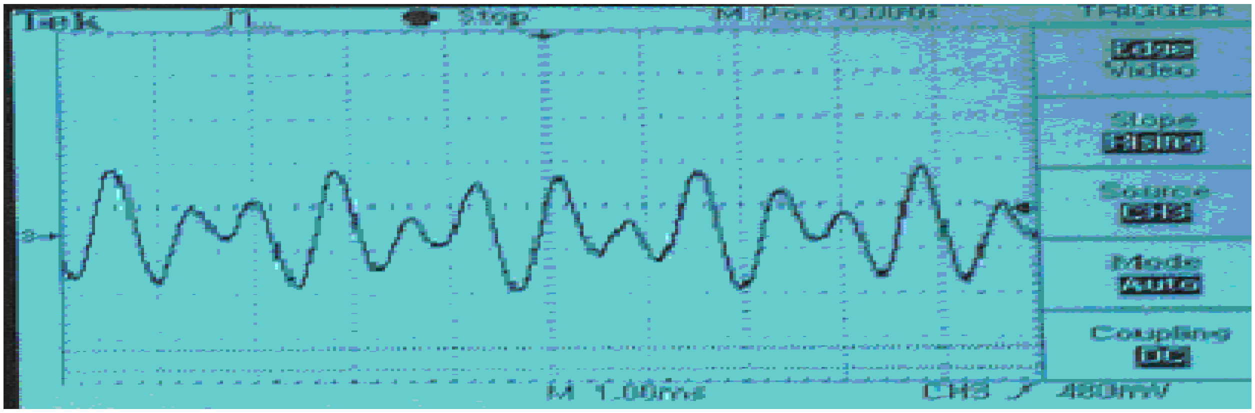

Figure 5. (A) Signal output from hardware.

Stage One – Output Verification

In the first stage of testing, the goal is to verify that a DTMF signal can be generated acoustically in air. A robot with DTMF transceiver is programmed to output a series DTMF characters. These characters can be heard as “beeps”. Using Matlab™ (The Mathworks, Inc.), a simulation of the DTMF signal was generated using equation (1) to compare against the result of the hardware generator. By inputting the correct overlaying frequencies, the results of simulation and actual output can be compared against one another. Figure 5 (A) and (B) show DTMF character “4” as output by the hardware in comparison with Matlab™ simulation result.

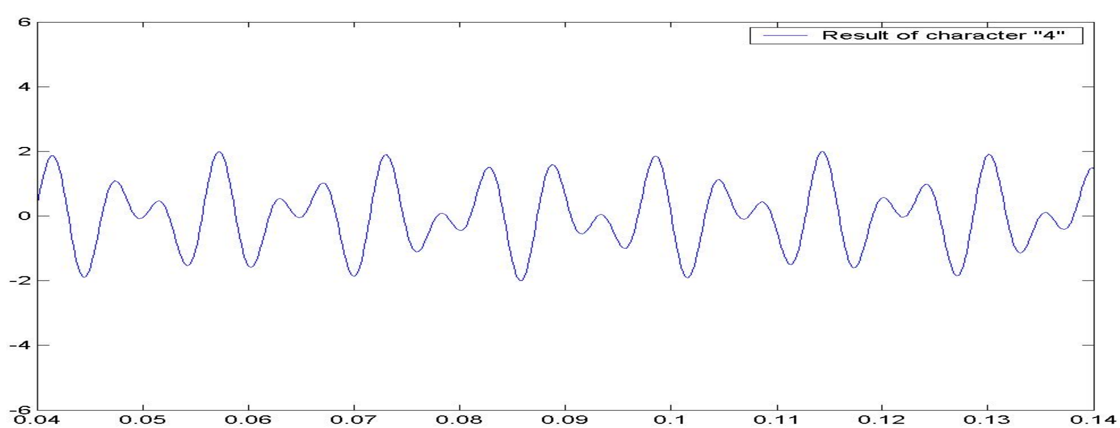

Figure 5. (B) Simulation result of DTMF-encoded character “4” – overlaying frequencies are 770 Hz and 1209 Hz.

By verifying that the hardware output matches with simulation result, we can confirm that DTMF encoded signals can be generated and acoustically sent into the air.

Stage Two – Testing of Data Transmission

To test the integrity of data transmission, we started out with a controlled setup testing before allowing the robots to operate in their test environment. In this setup, the robots are strategically placed to face one another on the table. The robots then go through a test algorithm where one sends and the other receives each DTMF characters. The robots are then moved to different locations as well as different facing to test robustness of signal transmission through air. It quickly becomes apparent that the communication integrity deteriorates quite fast when the distance between the robots increases – as shown in Figure 6. Test results also indicate that the sender/receiver alignment variation tolerance is very low. There is a drop-shaped region of effective communication where the robots can communicate reliably; this region is disappointingly small. An effective communication envelope was estimated as shown in Figure 7.

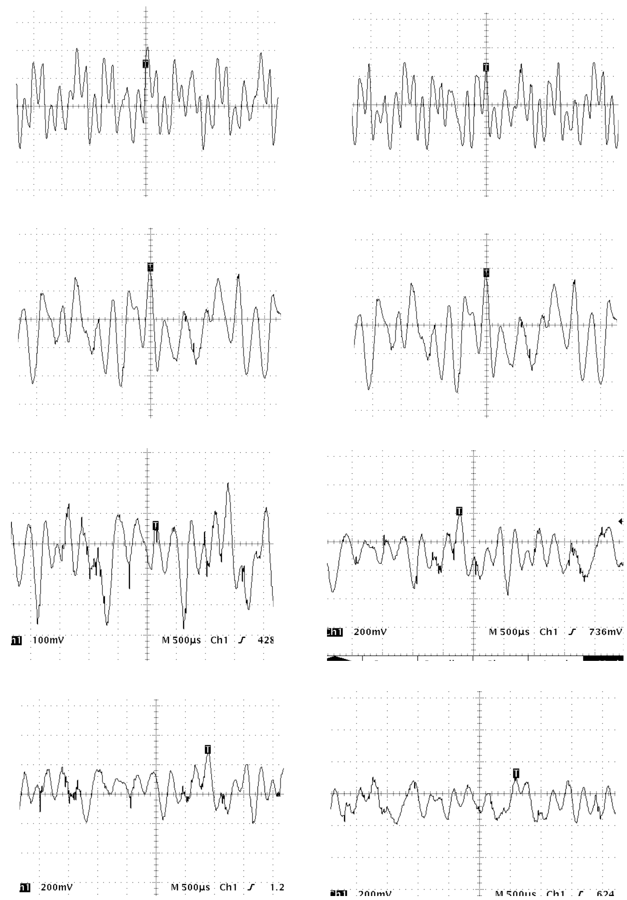

Figure 6 – Plots of DTMF signals as received by the receiver at 1, 1.5, 2, 2.5, 3, 3.5, 4, and 5 inches away from the speaker respectively from left-to-right and down

Remark: Different DTMF characters have different level of effectiveness in transmission, i.e., one DTMF tone may have a larger effective communication area than the other. Therefore, in estimating the effectiveness region of the whole DTMF character set, communication is considered failed when two or more tones out of 16 are not transmitted successfully.

Stage Three – Attempts at Navigating the Environment

Even though testing results from stage showed a highly restricted communication range, the decision was made to go ahead with testing of the third stage to quantify the maximum level of communication exchange that can be achieved and to see whether any surprises arise.

In stage three, two experiments are performed using two robots that are completely autonomous and mobile with onboard DTMF transceivers. The commands, as illustrated in Table 2, are directly represented by the DTMF characters. Since the main focus is an investigation into DTMF as a method of data transmission, no protocol was developed to package the signals. In a more complicated application, a protocol to combine the characters into more capable packets is necessary.

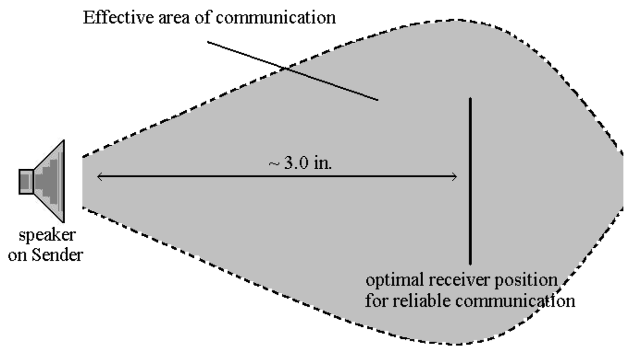

Figure 7. Estimated Effective Area of Communication.

Experiment # 1 – In the first experiment, two robots start out facing one another within their effective communication range. Robot #1 is designated to remain stationary and controls Robot #2 using commands encoded in DTMF tones. The simple commands are as illustrated in Table 2. Robot #1 begins by sending a command to Robot #2 to make a certain movement (i.e., move forward a predetermined distance). Robot #2 acknowledges the command, executes it, and then sends request back to Robot #1 for another command. Upon receiving the request, Robot #1 sends another command to Robot #2, and the cycle continues to test communication effectiveness between one stationary and one mobile robot.

Result from this experiment shows rapid breakdown of communication. The first robot was able to send the initial command (with acknowledge from the second robot), however, once the second robot moves out of range, communication cease to exist.

Experiment # 2 – The idea in the second experiment is to test communication when both robots are mobile. The robots start out facing each other and within one another's effective communication range. Robot #1 sends out the initial command to begin the communication exchange. Robot #2 acknowledges the first command then moves to a random position and then sends back a command to the first robot indicating that it has now moved to a new location. The Robot #1 acknowledges the message then makes its move to a random position and transmits another command to Robot #2 to signal that it has moved. The sequence repeats to test reliability of communication at different locations.

The result is that the initial start command was sent, received, and acknowledge correctly since the robots started out relatively close and face each other. However, as one robot moves out of the restricted range, communication breaks down immediately. This result is verified over several tests.

Supplemental Investigation – Microphone and Sound Transmission Properties

In an effort to gain more understanding into why the project failed to produce desired result, a supplemental investigation was conducted to look into properties of sound transmission through the air as well as the microphone's ability to pick receive the

DTMF Characters	0	1	2	3	*	#
Exp1 Commands	Forward	Backward	Turn_rgt	Turn_lft	Start	Stop
Exp2 Commands	Ack	Nak	New_pos	.	Start	Stop

Table 2. Simple commands for experiments 1 and 2 are mapped to each DTMF number.

sound. The investigation yielded two primary reasons behind the transmission failure. The primary causes are the crude amplification method used on the received signal and the condenser microphone's inefficiency in picking up high frequency signals that are low amplitude. These causes are discussed in detailed below.

Amplification failure – As the input signal is received by the microphone, it is amplified by a simple circuit before being read by the DTMF receiver. This is a linear gain circuit that is designed to simply amplify the input by a gain that is preset manually. Clearly, this means that the receiver can only be in an optimal distance away from the sender in order to effectively receive the signal and send to the decoder. An example of failure exist when the amplifier is set to amplified a sound transmitted from 5 inches away to the optimal level for the decoder but if the robot moves too close or too far from the source (sender), the amplifier output will either be clipped if too close or barely visible if too far.

An obvious solution for this problem is to design a smart input-sensing amplifier that is able to always produce a consistent output level regardless of input. Such amplifier can be purchased commercially or designed oneself. However, if one is to take this approach, a difficulty arises due to the DTMF signal being amplified is an asymmetric signal (from the overlaying of two frequencies). Therefore, knowing how much to amplify for each part of the signal is difficult (since the entire signal cannot be of the same amplitude). This difficulty can be overcome if the receiver somehow "knew" in advance how far the source is; however, this defeats the purpose of developing an alternate method of communication.

Microphone's Inefficiency – The second issue that arose during experimentation of the project is that the condenser microphone seems to be inefficient in picking up asymmetric/low-amplitude/high-frequency signals. More specifically, the microphone performs well when it is near the source of the signal. However, as the distance is increased, the signal is clipped. The trend is as shown in Figure 8 below.

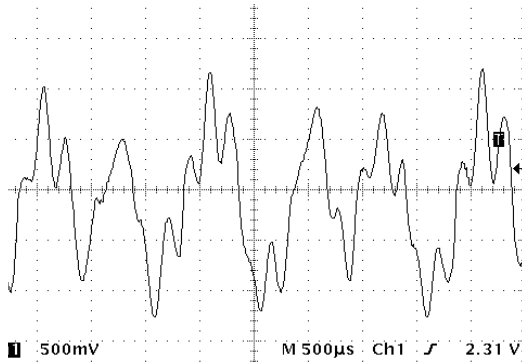

Figure 8A – From 1.5 inch away from source, the signal received has almost no noise

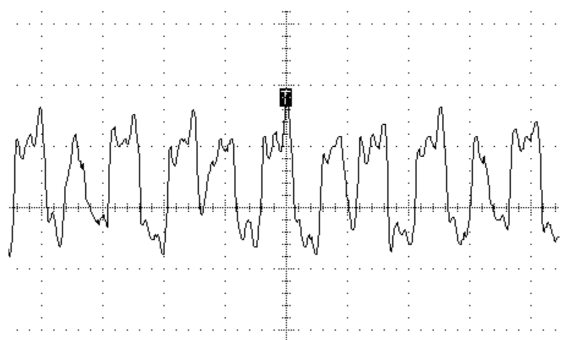

Figure 8B – Signal is moderately clipped at 5 inches away from source

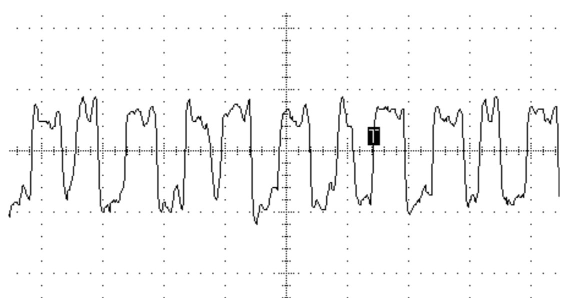

Figure 8C – Signal is clipped more severely at 10 inches away from source

As the trend from the graphs above indicates, the efficiency of a condenser microphone degenerates as distance is varied. This inefficiency seems to affect only the asymmetric part of the signal – the harmonics are still well represented. A possible explanation for this characteristic may be the limiting recovery ability of a condenser microphone's diaphragm from asymmetric vibration. More specifically, as the diaphragm is moved by a sound wave pushing on it, it relies on its own oscillation to spring back. However, if the sound is asymmetric, the recovery oscillation may be out of synchronization; hence; unable to represent the low-amplitude/high-frequency part of the signal. Further work on the microphone may be necessary to fully understand this complication; however, it is deemed outside the scope of this paper.

Overall Results

The following overall results were obtained from the experiments:

1. Communication is only reliable within 3 inches, with variations depending on other contributing factors such as amplification level (limited to power on the Handyboard) and whether the speaker is directly facing the microphone. Though a three-dimensional array transceiver could be set up to improve signal transmission capability, however, this array transceiver raises issues such as interference and phase shifts. It is decided that such array of transceivers is outside the scope of this paper.
2. With the specific components used (especially the condenser microphone), communication is highly directional. There is a small drop-shaped region of positions that the microphone can be situated to receive the signal reliably – However, this region is very small and the microphone also has to directly face the speaker to pick up the signal.
3. Communication breaks down rapidly when the sender, receiver, or both are in motion. Tests indicate that it is very hard to reestablish communication even when the robots are within range due to the requirement that the transceivers have to face one another.
4. Supplemental investigation into the signal transmission characteristics indicates difficulties with proper amplification of input and condenser microphone's inefficiency in receiving asymmetric signals.

From the results above, we decided that DTMF is not a good option to be implemented as a method of communication between mobile robots. Problem with sound disintegration in air causes the signal to lose integrity quickly. Furthermore, physical properties of acoustic sound transmission and properties of a condenser microphone further impose limitations on the quality of a signal received.

IV. Conclusions

This paper has described the design and implementation of experiments to test the feasibility of using the Dual Tone Multi-Frequency encoding scheme as a method for communicating simple messages acoustically. The experimental results have lead to the recommendation of not using DTMF or acoustical communication as a method for mobile robot information exchange. Many factors contribute to the shortfall of this idea. The main factors are, but not limited to, the nature of sound generation, transmission, degradation through air, amplification technique, and receiver technology. These limitations are further aggravated by the mobility of the robots.

Even though DTMF communication is deemed unsuitable as a communication method for mobile robots, there exist other areas where it should be more applicable. The authors propose using DTMF technology in applications where both robots are not mobile but rather a mobile robot communicating with other stationary devices. For example, in healthcare (hospital and home environments), a robot that is capable of sending acoustic commands to turn on/off devices such as light switch or closing door while letting the user know that the process is taking place will be very helpful in allowing the user to feel more comfortable around robots.

Furthermore, there also exists a movement toward simplifying networks away from the overly fast and complicated hardware and algorithm of today. These networks include large number of nodes that are very simple and act merely as relay stations. The nodes' primary responsibility is to pass along only necessary yet simple information, i.e., whether a unit being monitored is still functioning. DTMF acoustic communication would be an ideal implementation for this application. DTMF's advantages lies in its simplicity, low cost, as well as its already popular status in the telephone industry of today.

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