Design of Rodent Repellent Mobile Robot

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1. Introduction and Motivation

“It is a widespread and very popular belief, that however obnoxious an animal parasite may be, it has some compensatory feature attached to its existence; that in nature's scheme of affairs it fulfills some useful purpose. A thoughtful consideration of the rat, however, fails to reveal any redeeming feature that could justify a tolerance of this highly destructive and disease-bearing pest. Perhaps in other ages and under different sanitary conditions than now exist in civilized communities, the rat served as a much needed scavenger; but changing conditions have robbed the rat of even this questionable argument for existence”.

- Extract from Public Health Bulletin, No. 103, June, 1919,
New Haven Department of Health.

Rodents are among nature's most prolific mammalian breeders. Worldwide, 3.5 million rats are born every day. Female rats breed up to a dozen times in a year and produce, on average, a half-dozen offspring. Some litters total 20 or more. (1) The rat population in the United States is estimated to be 1.25 billion rats, possibly more.

It is impossible to calculate the extent of the damage inflicted by rats. The scope of the damage however, is immense. They destroy standing crops and harvested grain causing huge food losses even before the crop leaves the farm. Structural damage is caused by burrowing and gnawing rats. Rats once put out the lights at Heathrow airport by gnawing through double-insulated power cables.
Beyond such economic damage, however, rats pose health hazards. The animals harbour the lice and fleas that spawn serious diseases such as typhus, trichinosis, infectious jaundice and the deadly plague (1).

Owing to such high nuisance value, rodent control products have never been short of buyers. Traditional rodent control methods include poisoned baits, traps and rodenticides. However, traps eventually require the disposal of rat bodies and rodenticides run the risk of inadvertent secondary poisoning. Furthermore, these methods cannot be employed in places where the mere presence of a rodent, and the thereby, the smallest chance of urine and fecal contamination, cannot be tolerated (e.g. food storage warehouses, restaurants, etc.)

Hence, the pest control industry is overrun with electronic devices that claim to clear off existing rodent infestations and ward off future ones. These devices are usually static and target the victim of a domestic rodent infestation. The devices are meant to plugged into electrical outlets in the inflicted homes, upon which, they emit the alleged repellent stimulus. However, there is overwhelming evidence documented through numerous studies (from Sprock et al. in 1969 to Shumake et al. in 1995) regarding the gross inefficacy of these devices. As a result, the scientific community advises that these devices “be viewed with considerable scepticism by legislators, pest controllers, and consumer” (2).

Hence, it was proposed that the possibility of designing a rodent repellent device in the form of a mobile robot, that overcomes most of the disadvantages of static electronic devices, be explored.
1.1 Problem Statement

A complete problem definition or problem statement answers four questions:

a. What is the problem?

b. How can it be solved?

c. What resources can be used to solve it and what are the constraints on the resources?

d. What are the criteria that need to be satisfied to say that a problem no longer exists or is solved?

In this case, the problem was to design a mobile robot that repels rodents. An autonomous robot platform would carry repellent stimuli as payload. The product was not aimed at the domestic (household) market, but at the commercial market, where the economic losses and/or sanitation issues caused by rodents were far greater than the cost of the robot. Deployment areas would include grain storage silos, restaurant and supermarket warehouses, server rooms and cargo ships. It was critical that the robot be fully autonomous and its design and functioning be site-nonspecific. This was important, as the customer would not be skilled and could not be expected to customize the performance of the robot to suit the deployment site.

The repellent stimuli would be chosen after reviewing the work published in the area of pest control. In the initial version, the repellence would be passive; that is, the robot would not attempt to locate the rodents, but would rather patrol the area to be kept rodent-free and dispense repellent stimuli in a predetermined pattern. Even this initial version of the robot is expected to have better repellence efficacy compared to the products currently in the market.
This is due to the non-static nature of repellent stimuli and the use of multiple stimuli as a part of an integrated repellence strategy. Due to a lack of an industry standard on the measure of repellence, the definition of repellence is highly subjective. Hence, the design would be deemed successful if it displays a higher repellence efficacy than the products currently available on the market. The tests would be conducted as per standard federal test protocols which are described in later sections.

Furthermore, it has to be mentioned that the robot would be built as a ‘proof-of-concept’ and as an initial prototype. This assumption will govern a lot of design decisions which are further elaborated in chapter 3. Based on the preliminary concept design, a budget of $2640 CAD (all inclusive) was approved by Prof. Goldenberg.

1.2 Summary of Contribution

In this project, I was responsible for the selection of repellent stimuli and synthesis of repellence strategy. I also completed the conceptual design, mechanical design, fabrication and assembly of the mobile platform. Furthermore, I was responsible for the selection of navigation strategy and generation of algorithm to implement the chosen navigation strategy. The microcontroller programming was completed by my colleague at the Robotics and Automation Laboratory, Mr. Juzhong Zhang.
2  Review of Literature

The purpose of this literature review is to compile all the information that is necessary for the task of designing and building a rodent repellent mobile robot. The literature review is composed of two primary sections. The first section focuses on the repellence mechanisms that can be used and the protocols that have been used to test the repellence efficacy of these mechanisms. The second section deals with the mobile robotics aspect of the project and focuses on the information necessary to build a mobile platform that will carry these repellence mechanisms as payload.

2.1  Stimuli used in Repellence

Some of the mechanisms that have been previously explored for rodent control include audio stimuli, visual stimuli and chemical stimuli. The purpose of this section of the literature review is to survey the work done in the past with these mechanisms, compare and analyze the results of different studies, highlight the contradictions if any and if possible, synthesize an integrated rodent repellent strategy using a combination of some or all the mechanisms above.

2.1.1  Audio Stimuli:

Devices with audio stimuli utilize sound in audible frequencies as well as the ultrasonic frequencies. Extensive research has been performed over the years on the use of sound as a deterrent to mammalian pests in general (3), (2), (4) and rodents in particular (5), (6), (7).

In her review of the effectiveness of various devices using sonic stimuli as deterrents in animal damage control, Mary Bomford notes that very few experiments have been designed to test sonic devices and most publications on this topic describe field tests and demonstrations,
rather than controlled and replicated experiments. Also, contrary to the claims of most device manufacturers, although rodents can hear well into the ultrasonic range, there is no evidence to suggest that ultrasonic sounds or infrasonic sounds have special properties to repel rodents, compared to audible sound (2). Furthermore, almost all studies performed on rodents and other vertebrate pests indicate that after a period of time, these animals adjust to and ignore a new sound; a process called habituation. The use of multiple stimuli, applied in combination with one another, at random intervals for continuously varying durations is expected to delay the onset of habituation.

As observed by Bomford, the mechanisms used by sonic devices to allegedly repel animals include pain, fear, alarm and distress mimics (bio-sonics), ultrasound, communication jamming, disorientation, and internal thermal effects.

2.1.1.1 Pain as a repellence mechanism

Citing Kryter 1970, Pinel 1972, Shumake et al. 1982, Georg 1985 and Beuter and Weiss 1986, Bomford states that audible sound above 130 dB and infrasonic or ultrasonic sound above 140 dB cause pain and sometimes sickness in vertebrates. Also, it is technically difficult and expensive to produce and radiate sound at levels greater than 130 dB (Beuter and Weiss 1986 as cited by Bomford 1990). Furthermore, audible sound at high intensities is likely to be a nuisance to people and the use of pain to repel rodents may provoke objections from animal welfare groups. For these reasons, audible sounds, at pain inducing intensities has little potential for pest control (2).
2.1.1.2 Bio-sonics as repellents

Bioacoustics is defined as the study of biologically significant sounds originated by animals, and the mechanisms which produce and receive these sounds. Bioacoustics as it is applied to the control of pests is popularly called bio-sonics (8). Specifically, the field of bio-sonics deals with ‘distress calls’ and ‘alarm calls’. Distress calls are sounds emitted by rats when restrained or caught by a predator. Experiments designed to test the habituation rates and relative aversion of various recorded calls show that wild-caught starlings display greater aversion to taped distress calls compared to pure tone sounds of equivalent amplitude. Also, the starlings were exposed to 3 times as many applications of distress calls than other sounds before habituation was observed (2). This observation has been common to a number of other studies and leads to the conclusion that alarm or distress calls are more resistant to habituation than other sounds.

Studies show that low-frequency 22-kHz ultrasonic vocalizations (USV) are emitted by adult rats when exposed to predators (9), or other aversive stimuli, like startling noises (10), or inescapable foot-shocks (11). Such vocalizations are not only emitted during the actual aversive event, but also in response to stimuli associated with such experiences (11) Thus, playback of these USV’s can be used as a repellent stimulus.

Furthermore, controlled experiments have also been conducted to study the effects of bio-sonics on wild rats. It was observed that wild rats stayed away from a sound chamber in which a recorded distress call of rats being fed to a skunk was being played. The rats preferred to stay in a control chamber in which no sound was being played. These experimental results were seen as an indication of the effectiveness of distress calls in controlling rats (5).
Hence, bio-sonics scores over other sonic mechanisms in repelling rodents in two respects: its scientifically proven effectiveness of repellence and its higher resistance to habituation. Hence, bio-sonics can play a central role in the desired integrated rodent repellent strategy.

2.1.1.3 Non-biosonic devices with audio stimuli

Non-biosonic devices with audio stimuli utilize the tendency of pests to perceive novel sounds as dangerous and generally avoid them; a phenomenon termed as neophobia (2). These devices include various crackers, bangers, sirens and electronic noises, all in the audible frequency range. Tests conducted to gauge the response of rats to sonic stimuli concluded that white noise was aversive at 85 dB; pure tones were aversive at 105 dB but also produced immobility in rats (2).

The body of research on the use of non-biosonic, fear-inducing sounds for pest control, as summarized by Bomford, reinforces the intuitive conclusions that (1) loud sounds are more aversive than quiet sounds and (2) sounds with a wide frequency range are more aversive than pure tones. It also suggests that the best effects are obtained when (1) sound is presented at random intervals; (2) a range of different sounds is used; (3) sound source is moved frequently (4) sounds are supported by other methods like distress signals, visual devices and (5) sounds are reinforced by real danger.

The research also shows that all species habituated to nearly all sounds tested and hence the use of these sounds is entirely limited to short term control. The difficulties associated with producing white noise and pure tone sounds at the desired levels (85 dB and 105 dB
respectively); combined with the adverse effects of exposure to such high levels of sounds on humans, make this mechanism somewhat impractical for use with the integrated rodent repellent strategy.

2.1.1.4 Ultrasound Repellence

Ultrasound (sound frequencies ≥ 20 kHz) is perhaps the most extensively researched and by consequence, the most controversial mechanism for rodent repellence. Contrary to the frequent implication, ultrasound has no special property that makes it more aversive to pests than audible sounds (2). Many studies have rejected ultrasound as a practical means of rodent control. They have found that ultrasound either had no effect on the target species (birds) or had a partial or transient effect (mammals) (2).

A 1982 study by S. A. Shumake analyzing the repellence efficacy of 3 ultrasound devices (20 kHz fixed frequency, 20-30 kHz frequencies, 40 kHz fixed frequency) yielded the following result. The 20 kHz device was as effective as 20-30 kHz and 40 kHz devices when the food was freely available. However, when food was scarce, the 20 kHz device had no repellence whereas the other devices provided some repellence. The devices were not tested for habituation.

With regards to the rate of habituation to ultrasound, it has been observed that while rodents may temporarily avoid areas “covered” with ultrasound, they habituate to the ultrasound and will feed or nest alongside the operating devices (3).

At least 2 independent studies on ultrasound repellence [(5), (6)] observe that it may be extremely difficult to develop acoustical frightening devices that will effectively eject rodents from infected premises, since rodents easily habituate to new sounds. Both the studies concur
that it might be easier to utilize ultrasound to discourage rodents from approaching the source of sound, if the animals have never been on the other side of the sound barrier. Thus, if sonic fields are placed across all routes of ingress into the rodent free premises, re-infestation might be avoided. However even Greaves and Rowe admit that a few rats and mice might not be completely deterred and such animals, in addition to others that might be carried into the premises in commodities, could remain as possible sources of infestation.

2.1.2 Observations on the use of Audio Stimuli

The conclusions of various experiments involving the use of audio stimuli for rodent repellence, which were studied during this literature review, can be summarized as follows.

a. Reinforcing distress calls with other danger stimuli reduces the chances of habituation (3).

b. Both frequency and intensity of ultrasound are necessary components for producing feeding repellence (7).

c. 20 kHz device could be potentially effective in reducing feeding and rat habitation where there is abundant food or where there has been an existing, undisturbed rat infestation. When the rats’ food is restricted, the 20-30 kHz and 40 kHz devices proved to be more effective (7).

d. Continuous sound pressures of less than 120 dB at any frequency from 4 kHz to 16 kHz proved to be ineffective in deterring wild rats in the experiment (5).
e. From a practical standpoint, all ultrasonic rodent repellent devices are quite limited in their effective range, because the energy is quickly dissipated and does not normally reach occluded areas unless reflective surfaces are available (7).

2.1.3 Chemical Stimuli:

Chemical irritants use sensory irritation, semiochemical mimicry and gastrointestinal malaise as mechanisms producing repellence (4). Each of these mechanisms is discussed in detail below.

2.1.3.1 Sensory Irritation

Rodents utilize olfactory cues to locate food items, recognize their mothers and mates, mark territory, recognize predators, identify toxic substances or repellents (12). Sensory irritation is the irritation of the eyes and the upper airways when inhaled. Sensory irritants are nearly always more effective repellents than semiochemicals or malaise causing substances. Irritants are globally effective within taxonomic groups. However, there exist marked differences in the perception and sensitivity between taxa. This implies that irritants used to repel rodents (mammals) are as likely to affect humans. Common sensory irritants for mammals include capsaicin (10-100 ppm concentration), allyl isothiocyanate (active ingredient in mustard, tear gas) (4). Also, contrary to popular recommendations, aniseed oil, peppermint oil and n-butyl nercaptan were deterrents to wild rats. The strength of an odour used is important, as attraction or repulsion depends of the strength of the odour (12).
2.1.3.2 Semiochemical Mimicry

A semiochemical (semeon means ‘a signal’ in Greek) is a generic term used for a chemical substance or mixture that carries a message. It is usually used to encompass pheromones, allomones, kairomones, attractants and repellents (13).

Extensive laboratory and field studies by Sullivan and co-workers, testing a number of synthetic components of predator scent, resulted in a potential new rodent repellent comprised from two constituents of mustelid anal gland secretion. Both of these secretions contain sulphur (14).

2.1.4 Visual Stimuli:

A variety of visual stimuli is used to repel pests. These stimuli include lights, movements and/or various reflective objects (3). Since most serious mammalian pests are nocturnal or operate in generally dark environments, a variety of continuous, flashing, revolving or strobe lights are used to repel these pests. Predator models that take advantage of naturally occurring predator-prey relationships can be used to repel rodents (3).

However, the rapid rate of habituation that is usually observed with visual stimuli restricts their usefulness over the long-term. Furthermore, unless inanimate predator models are reinforced in a meaningful fashion, they are unlikely to be perceived as an actual threat for long.

The problem of habituation to visual and indeed any kind of novel stimuli can be partly solved by diversification and variation. These are key elements in prolonging the time to habituation. Also, motion makes the predator models appear more threatening and hence delays the habituation to these models.
As noted by other researchers with regard to sonic and chemical repulsion mechanisms, Koehler (1990) observes that visual repellents are more powerful when used as components of integrated pest management strategies.

2.2 Efficacy Testing of Rodent Repellent Devices

When the proposed rodent repellent robot is built, it will have to be tested as per various federal test protocols that govern all products designed to manage, destroy, attract or repel pests. This section intends to shed some light upon the testing of rodent repellent devices. A summary of means and methods used in notable experiments in this area, over the past decades, is also provided.

2.2.1 Test Environments:

Testing of rodent repellent devices can be carried out in 3 environments. Depending on the stage of advancement of the testing process, testing can be carried out in a laboratory, an enclosure or in the field (15). These environments are further explored in detail below.

2.2.1.1 Laboratory:

Test chamber setups are a good place to start testing a rodent repellent device. External conditions such as food abundance or scarcity, temperature and phenomena such as the day-night cycle can be conveniently simulated in test chambers. Test chambers allow for better control over test parameters as compared to enclosure or field settings. Further, laboratory setting allows for the study of individual animal responses such as head movements, jumping, running and escape, in greater detail (15).
Consequently, due to the confined nature of the testing environment, wild rodent test subjects are observed under conditions that are quite unlike their natural habitat. Hence, confinement stress and unfamiliar surroundings cause the rodents to exhibit altered behaviour and altered physiological responses, which can be greatly diminished or exaggerated versions of their natural responses. This will cause extremely varied response to the same stimuli. Furthermore, factors like predator-prey interactions, interspecific and intraspecific competition, which significantly affect the results of such experiments, cannot be studied in a laboratory or even an enclosure setting. Similarly, factors such as rodent density and breeding competition cannot be studied in a laboratory and require an enclosure environment (15).

Devices used to record escape or avoidance response (as a consequence of repellence) include treadle-switch chambers, proximity detectors (14) and photoelectric devices (5). Although these devices possess an inherent advantage of operational simplicity, each of these devices comes with associated disadvantages with regards to their use in rodent testing. Treadle-switches may make a distinct ‘clicking’ sound when operated, which may be a repellent in itself to some test specimens, leading to confounded results. Photoelectric devices get rid of this effect, but are susceptible to false counting signals due to rats twitching their tails in the photoelectric beam (5). However, with massive advances in sensor technology in the last decade, a host of highly sophisticated sensing devices are now available to the modern experimenter. These include laser sensors, motion sensors, infra-red sensor arrays, etc.
An indirect measure of repellence can be obtained through ‘fear’ or ‘disturbance’ levels of the test subjects using parameters such as heart rate acceleration and decreased rate of food-reinforced lever pressing (14).

2.2.1.2 Enclosures:

As stated before, the effects of social interaction, population density, and breeding competition can be studied only in enclosure (or field) settings. Furthermore, repellent signals could sometimes have a ‘contagious’ effect on a group of rodents, which cannot be studied with individual rodents or in laboratory settings (15).

An enclosure setup for efficacy testing of rodent repellent devices usually consists of multiple chambers with interconnecting pathways. Rodent test subjects are free to move from one chamber to another using these pathways. The number of chambers depends on the number of devices that are to be tested simultaneously; each chamber housing one device. In addition, there is also a chamber called a ‘control’ chamber, which houses an inactive device. This chamber serves as the reference for the experiment. Identical food, bedding, lighting and temperature conditions are provided in all chambers. Figure 1 shows the setup used by Shumake et al. in the experiments described in Shumake’s study on Philippine rats (7).

Parameters that are measured to evaluate animal presence and hence repellence include general activity, food and water consumption, fecal pallet counts, urine spots and nesting activity signs and animal tracking board activity. (15). Chalk dust or flour can also be used to cover the floor of the enclosure to detect animal activity. (16). Initial approach or avoidance
into the enclosure has shown better correlation with field data as compared to other parameters such as general activity or food consumption. (15).

For multiple chamber setups, devices like treadle-switch chambers, proximity detectors, laser sensors, motion sensors and infra-red sensor arrays can be used to measure time spent by rodents in each chamber. Often, the general activity of the rodents is recorded on tape and then analyzed for signs of avoidance behaviour and repellence. Instances of such behaviour can then be measured and tabulated for further statistical analysis, as in the case of the experiments conducted by Greaves et al. on confined rodent populations (6).

Figure 2.1 The experimental test facility for simultaneous comparison of rat responses to 3 ultrasonic devices (U1 - U3) vs. control (C). (7).
Experiments can be designed to test the repellence effect of devices under various conditions such as plentiful food vs. restricted food, continuous vs. discontinuous sound, native rat population (rats that have been acclimatized to the enclosure) vs. immigrant rats (rats who have not been acclimatized to the enclosure) (7). The third set of conditions is especially interesting as it allows us to evaluate the efficacy of a device in preventing rodent infestations, along with its efficacy in clearing out an existing infestation.

2.2.1.3 Field Tests:

The ultimate aim of all rodent repellent devices is to achieve repellence in real-world scenarios. Field efficacy tests come closest to emulating circumstances that the device will operate under in the real world. Therefore, it is not surprising that any electronic device that is to be used for rodent control in Canada must pass field tests to demonstrate its efficacy before it can be registered and sold commercially.

Field tests are performed at sites that have naturally existing rodent infestation. Parameters that are measured in field tests include animal counts (by direct observation or videotaping), food consumption or disturbance, fecal pallet counts and rodent activity detection. (15). Other means used to detect rodent activity include photo-switches and covering the floor of the test site with baking flour or chalk dust.

2.3 Mobile Robotics

Due to the vast nature of the topic and in the interests of brevity, the literature review on mobile robotics has been greatly condensed. However, effort has been made to include
pertinent information as and when required in the next chapter. This section focuses on some locomotion strategies used by wheeled robots.

2.3.1 Locomotion

Locomotion is the process of causing an autonomous robot or vehicle to move. Based on the design of a mobile robot, there exist a variety of locomotion strategies. However, the choice of a particular locomotion strategy is primarily based on its application and its domain. It depends on several factors like ‘is the application primarily indoor or outdoor?’, ‘is the robot expected to climb stairs?’, ‘how much area would it cover under normal course of its operations?’ etc. Based on the domain of application, there are four major categories of mobile robots: terrestrial, aquatic, airborne and space. (17). Since our application domain would most likely be solid ground, we will focus on terrestrial robots for the purpose of this review. Terrestrial robot platforms may have wheels, limbs or tracks for locomotion. Nature favours legged locomotion, because of its ability to deal with rough and unstructured terrain. In contrast the human environment frequently consists of engineered, smooth surfaces, both indoors and outdoors. Therefore virtually all commercial applications of mobile robotics utilize some form of wheeled locomotion (18). We will now look at some popular drive systems for wheeled mobile robot platforms.

2.3.1.1 Differential Drive

Differential drive robots, in their most basic form, consist of two wheels mounted on a common axis, controlled by separate motors. Under differential drive, for each of the two wheels to exhibit rolling motion, the robot must rotate about a point that lies on the common axis of the
two drive wheels. By varying the relative velocities of the two wheels, this point of rotation can be varied and different trajectories can be chosen (17).

The name refers to the fact that the motion vector of the robot is sum of the independent wheel motions, something that is also true of the mechanical differential. A non driven wheel, often a castor wheel, forms a tripod-like support structure for the body of the robot. Unfortunately, castors can cause problems if the robot reverses its direction. Then the castor wheel may turn half a circle and, in the process, the offset swivel may impart an undesired motion vector to the robot. This may result in to a translation heading error. Straight line motion is accomplished by turning the drive wheels at the same rate in the same direction (18).

Kinematics of differential drive robots are illustrated here. Position at time ‘t’, relative to a known initial position, can be calculated using simple equations. Suppose that at sampling interval $i$ the left and right wheel encoders show a pulse increment of $N_L$ and $N_R$, respectively. Suppose further that

$$C_m = \frac{\eta \pi D_n}{C_e}$$

Where,

$c_m$ = conversion factor that translates encoder pulses into linear wheel displacement

$D_n$ = nominal wheel diameter

$C_e$ = encoder resolution (in pulses per revolution)

$\eta$ = gear ratio of the reduction gear between the motor and the drive wheel.
We can compute the incremental travel distance for the left and right wheels, $\Delta U_{Li}$, $\Delta U_{Ri}$, according to

$$\Delta U_{L/Ri} = c_m N_{L/Ri}$$

and the incremental linear displacement of the robot's centre point $C$, denoted $\Delta U_i$, according to

$$\Delta U_i = \frac{(\Delta U_{Li} + \Delta U_{Ri})}{2}$$

Next, we compute the robot's incremental change of orientation

$$\Delta \phi_i = \frac{(\Delta U_{Ri} - \Delta U_{Li})}{b}$$

where $b$ is the wheelbase of the vehicle, ideally measured as the distance between the two contact points between the wheels and the floor.

The robot's new relative orientation $i\phi$ can be computed from

$$\phi_i = \phi_{i-1} + \Delta \phi_i$$

and the relative position of the center point is

$$x_{Ci} = x_{Ci-1} + \Delta U_i \cos \phi_i$$

$$y_{Ci} = y_{Ci-1} + \Delta U_i \sin \phi_i$$
Figure 2.2 Computing the position and pose

where

\[ x_{C,i}, y_{C,i} = \text{relative position of the robot's centre point } c \text{ at instant } i. \]

The velocity of the center point can be obtained from the wheels linear velocities as

\[ v_c = \frac{(v_R + v_L)}{2} = \frac{D_n(\omega_R + \omega_L)}{4} \]

where \( \omega_R \) and \( \omega_L \) are the right and left wheel angular velocities, respectively. Also, the angular velocity of the platform is derived as

\[ \phi_c = \frac{(v_R - v_L)}{b} = \frac{D_n(\omega_R - \omega_L)}{2b} \]

It is assumed that the wheels have an ideal rolling performance without any longitudinal or lateral slippage. Therefore, the velocity of the center line must remain along the platform's longitudinal axis, as shown in the figure. This condition imposes a kinematic constraint on the platform's motion, i.e.,

\[ \dot{x}_c = v_c \cos \phi \]
\[ y_C' = v_C \sin \phi \]

Combining the above two equations results in

\[ x_C \sin \phi - y_C \cos \phi = 0 \]

The above equation cannot be integrated analytically to obtain a relationship between the configuration variables, namely \( x_C, y_C \), and \( \phi \), and perhaps eliminate one of them in the kinematic and dynamic equations. Thus, the above condition is called non-holonomic constraint, which causes two independent variables in the velocity space while the configuration space contains three independent variables \(^{(19)}\). The physical implication is that a platform with the differential drive cannot have an immediate side motion, as illustrated in figure below

![Figure 2.3 Physical implication of non-holonomic constraint (19)](image)

Differential drive is known for its mechanical and operational simplicity and ease of implementation.

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2.3.1.2 Synchronous Drive

An innovative configuration known as ‘synchronous drive’ features three or more wheels mechanically coupled in such a way that all rotate in the same direction at the same speed, and similarly pivot in unison about their respective steering axes when executing a turn, as shown in figure below. This drive and steering synchronization results in improved odometry accuracy through reduced slippage, since all wheels generate equal and parallel force vectors at all times. The required mechanical synchronization can be accomplished in a number of ways; the most common being a chain, belt, or gear drive. Carnegie Mellon University has implemented an electronically synchronized version on one of their Rover series robots, with dedicated drive motors for each of the three wheels (19). Chain and belt-drive configurations experience some loss of steering accuracy and alignment due to uneven distribution of slack, which varies as a function of loading and direction of rotation. In addition, whenever chains (or timing belts) are tightened to reduce such slack, the individual wheels must be realigned. These problems are eliminated with a completely enclosed gear-drive approach. An enclosed gear train also significantly reduces noise as well as particulate generation, the latter being very important in clean-room applications.

![Figure 2.4 Synchronous Drive Train](image)
Referring to the above figure, drive torque is transferred down through the four steering columns to the wheels. The drive-motor output shaft is mechanically coupled to each of the steering-column power shafts by a heavy-duty timing belt to ensure synchronous operation. A second timing belt transfers the rotational output of the steering motor to the three steering columns, allowing them to synchronously pivot throughout a full 360-degree range. The upper head assembly is mechanically coupled to the steering mechanism in a manner illustrated in figure above, and thus always points in the direction of forward travel.

![Figure 2.5 Offset wheel to avoid slippage](image)

The disadvantages of this particular implementation include odometry errors introduced by compliance in the drive belts as well as by reactionary frictional forces exerted by the floor surface when turning in place. To overcome these problems, some mobile bases employ an enclosed gear drive configuration with the wheels offset from the steering axis as shown in
figure above. When a foot pivots during a turn, the attached wheel rotates in the appropriate
direction to minimize floor and tire wear, power consumption, and slippage. Note that for
correct compensation, the mitre gear on the wheel axis must be on the opposite side of the
power shaft gear from the wheel as illustrated. The governing equation for minimal slippage is

\[ \frac{A}{B} = \frac{r'}{r} \]

where

- \( A \) = number of teeth on the power shaft gear
- \( B \) = number of teeth on the wheel axle gear
- \( r' \) = wheel offset from steering pivot axis
- \( r \) = wheel radius.

The odometry calculations for the synchronous drive are almost trivial; vehicle heading is
simply derived from the steering-angle encoder, while displacement in the direction of travel is
given as follows:

\[ D = \frac{2\pi N}{C_e} R_e \]

where

- \( D \) = vehicle displacement along path
- \( N \) = measured counts of drive motor shaft encoder
In this section we will look at the design and selection of various components of our robots.

### 3.1 Chassis Design

#### 3.1.1 Motivation

An automotive chassis is a skeletal frame on which various mechanical parts like engine, tires, axle assemblies, brakes, steering etc. are bolted. The chassis is considered to be the most significant component of an automobile. It is the most crucial element that gives strength and stability to the vehicle under different conditions (20). The chassis is as important to the rigidity and stability of a mobile robot platform as it is to an automobile. In the context of a mobile robot platform the functions of a chassis are,

a. Serve as a rigid support and mounting surface for gear-motors, support castors and other load-bearing members.

b. Serve as a support surface for the mounting plate (plate on which all components, other than the gear-motor assembly, such as the microcontroller, motor controllers, battery are mounted)

c. Serve as a base for all structures that may be built on top of the mounting plate.

This section discusses the design of the mobile robot chassis.
3.1.2 Conceptual Design

The design of the chassis evolved from a simple annular structure to its current shape. All changes were strictly functional and were brought about to optimize the stability and rigidity of the mobile platform, while reducing its size footprint. The concept design went through 3 distinct phases.

Shape: Why round?

The shape of a mobile robot chassis is extremely critical. Round is usually the best shape, especially in the case of differential drive robots. Due to the drive geometry and non-holonomic nature of the differential drive, a large fraction of the robot’s motions would involve spinning in place to attain correct orientation. Hence it would make sense to not have any corners on the chassis that may cause manoeuvrability issues in tight spaces. The figure below illustrates this with an example. A square and a round robot with identical width are moving from left to right. The square robot has a greater risk of being trapped by an obstacle or failing to finds its way through a narrow space (18).

![Figure 3.1 Round versus Square - Maneuverability in tight spaces (18)](image-url)
**Phase 1: Annular Design**

In this phase, the chassis was shaped like a sliced donut. This shape was arrived at by removing all the material from the centre of a round plate for the purpose of saving weight, without sacrificing a lot of rigidity. Motors were mounted on diametrically opposite ends, on the ring, with shafts pointing outwards. It was immediately obvious that this design was not very compact and would cause issues in manoeuvring in tight spaces. This was due to the motor shaft and the wheels sticking out of the annular frame. If the motor was mounted the other way around, with the motor shafts pointing inwards, towards each other, wheels were too close to each other and the stability of the platform was compromised.

It was clear that the motors could not be mounted on the ring. Hence the annular design was modified.

![Figure 3.2 Chassis Design - Phase 1](image-url)
Phase 2: Modified Annular Design

The motors had to be mounted further in towards the centre of the ring along the diameter. As a consequence, the chassis was modified from an annular design to include a bridge that spanned the diameter, leading to the next phase of the concept design.

In this phase, the motors were mounted on the bridge. The bridge allowed the motor mounting positions to be moved laterally along the diameter. The motors could be mounted much closer to each other with their shafts pointed outwards. This allowed us to retain the wide wheelbase that brought stability to the platform, while maintaining a compact design, as the wheels did not stick out of the chassis to the same extent as before.

Phase 3: Recessed Wheel Design (Final Design)

In order to achieve a more compact design, the wheels would have to be recessed into the chassis. The ends of the bridge were modified by allowing curved slots to accommodate the
wheels. This allowed the motors to be mounted even closer to each other on the bridge and created the most compact yet stable design.

Figure 3.4 Chassis Design - Phase 3

This was the final design selected for execution. In the final design, the thickness of the plate was decided as 5 mm. The diameter was decided as 350 mm. This size was chosen to accommodate all the peripheral devices that were to be mounted on the robot, like the

Figure 3.5 Chassis with Motor and Wheel Assembly - Compact Design
microcontroller, battery, motor controllers, strobe, ultrasonic amplifier and transducer, mp3 integrated chip, etc. The material was chosen to be Aluminum Alloy EN AW-1050A due to its very good atmospheric corrosion resistance, very good workability and suitable for anodizing (21).

The microcontroller, motor controllers, battery and strobe were mounted on the first level mounting plate, which itself was mounted on the chassis. The IR sensors, ultrasonic amplifier, transducer and mp3 board were mounted on the second level mounting plate which was stacked on the first level plate.

3.2  Motor Sizing and Selection

The most critical aspect of mobile platform design is the calculation of the power and torque required for correct operation of the platform and subsequently, choosing the correct motor for the job. As this robot was a ‘proof-of-concept’ prototype, motor longevity was sacrificed in favour of low cost. Hence, we decided to restrict our search to geared DC brush motors (which are economical, but subject to brush wear issues) in place of brushless DC motors (which are expensive, but guarantee a longer and maintenance-free life). Stepper motors and DC servo motors were ignored due to cost constraints. Planetary gearbox was selected as it offers the higher gear ratio compared to spur gearbox of the same size. Motor was selected based on the results of torque requirement and RPM requirement calculations.

The calculations carried out for determining the torque requirements are detailed below. All calculations have to be carried out at the worst case scenario. For motor torque requirements, this arises when the robot is accelerating up an incline. We first carried out the calculations for
a general case and arrived at an expression for motor torque as a function of various parameters. We then plugged in actual values of those parameters, as decided by the specifications to arrive at the final value of required torque.

### 3.2.1 Torque Requirement Formulation

Let,

\[ m = \text{mass of the complete robot including motors}, \]

\[ \theta = \text{angle of incline} \]

\[ v_m = \text{maximum velocity of robot} \]

\[ t = \text{time taken to reach maximum velocity} \]

\[ a = \text{acceleration of robot up the incline} \]

\[ T_t = \text{total torque required} \]

\[ T = \text{torque required per motor} \]

\[ n_m = \text{number of motors} \]

\[ \eta = \text{efficiency of motor and gearbox} \]

\[ r = \text{wheel radius} \]

\[ \mu_r = \text{co-efficient of rolling friction between wheel and ground} \]

\[ g = \text{acceleration due to gravity} \]
A free body diagram (FBD) of the robot accelerating up an incline was drawn. From the FBD, summation of forces along the X-axis equals the mass of the robot times the acceleration of the robot along the X-axis.

\[
\sum F_x = m \ a
\]

\[
\therefore -\mu_r mg \cos \theta + \frac{T_t}{r} - mg \sin \theta = m \ a
\]

\[
\therefore T_t = [mg (\sin \theta + \mu_r \cos \theta) + m \ a] r
\]

This gives the total torque requirement for the task.

The torque required per motor is given by

\[
T = \frac{T_t}{N} = \frac{[mg (\sin \theta + \mu_r \cos \theta) + m \ a] r}{N \ \eta}
\]

Figure 3.6 Free Body Diagram - Robot accelerating up an incline
3.2.2 Robot Performance Specification

As discussed earlier, a general expression for torque required per motor was obtained. To calculate the actual torque required per motor, certain specifications for the robot performance will have to be decided.

- Desired maximum velocity ($v_m$): Based on the robot function (patrolling the perimeter while dispensing stimuli) $v_m$ is set to 0.8 m/s.
- Acceleration (a) is set to 0.4 m/s²
- Wheel radius: Higher wheel radius will reduce the rpm requirements of motor but will also increase the torque requirements. Wheel radius cannot be varied arbitrarily as it depends on the standard sizes available on off-the-shelf wheels. All other parameters kept constant, this parameter was varied as per the wheel sizes available in order to minimize the torque requirements and hence the cost of the motor. Optimum wheel diameter was found to be 32mm.
- Mass of the robot including the motors was assumed to be 8 kg based on SolidWorks estimates of preliminary concept designs.
- Motor and gearbox efficiency was obtained from the motor datasheet = 0.65.
- Co-efficient of rolling friction, $\mu_r$, was referred from online design data sources to be 0.015 (22)
- Number of motors = 2 in this case, for a differential drive
- Maximum angle of incline that the robot could approach ($\theta_m = \text{atan}[h/L]$) was limited by the geometry of the design of the robot, as illustrated below. $\theta_m$ depended on the wheel diameter and chassis diameter. For the optimum wheel diameter = 32mm and chassis
diameter = 350 mm, θₘ was calculated as 18°. For the ‘worst-case-scenario’ calculation, θ was assumed to be equal to θₘ = 18°.

![Figure 3.7 Geometric Constraint on θ](image)

### 3.2.3 Torque, RPM and Power Requirement Calculations

Based on the specifications described above, the torque required per motor (T) was calculated.

\[
T = \frac{T_t}{n_m} = \frac{[mg(sin\theta + \mu_r \cos\theta) + ma]r}{n_m \eta}
\]

\[
T = \frac{[8 * 9.81 * (sin 18 + 0.015 * cos 18) + 8 * 0.4] * 32}{1000 * 2 * 0.65}
\]

\[
T = 0.79 N - m
\]

As detailed in 1.1.1.2, the desired maximum velocity, \(v_m = 0.8 \text{ m/s}\). Converting to RPM, the desired maximum velocity in RPM (N)

\[
N = \frac{60 \cdot v_m}{2\pi r} = \frac{60 \cdot 0.8}{2\pi \cdot 0.036} = 212.2 \text{ RPM}
\]

The power required would be given by
Hence, we were looking for a motor that would run on 12VDC (battery supply voltage) and could supply a torque of at least 0.79 N-m at a speed of 212.2 RPM. However, motor data sheets usually provide only the stall torque and the no-load RPM. Hence, torque-speed, power-speed and power-torque curves for various motors were plotted based on the stall torque and the no-load RPM, using the following relations

\[
P = T\omega = \frac{Tv}{r} = \frac{0.79 \times 0.8}{0.036} = 17.55 \text{ Watt}
\]

\[
T = T_{PK} - \frac{T_{PK}}{N_{NL}} \cdot N
\]

\[
P(N) = -\frac{T_{PK}}{N_{NL}} \cdot N^2 + T_{PK} \cdot N
\]

\[
P(T) = -\frac{N_{NL}}{T_{PK}} \cdot T^2 + N_{NL} \cdot T
\]

Where,

\(T_{PK}\) = Stall (Peak) torque

\(N_{NL}\) = No-load speed in RPM

\(P(N)\) = Power as a function of speed N

\(P(T)\) = Power as a function of speed T
Figure 3.8 Torque - Speed Curve
Figure 3.9 Power-Speed Curve
Figure 3.10 Power-Torque Curve
As shown in the torque-speed graph above, motor with stall torque of 1.345 N-m and no-load speed of 818 RPM could supply a torque of 1 N-m at 212 RPM which is 26% more than the worst case torque requirement. The motor selected was the Banebots Planetary Gearmotor with RS-385 motor. The gear motor and its specifications are shown below.

![Banebots 7.2V 818RPM 190oz-in Planetary Gearmotor w/RS-385 Motor Specifications](image)

Figure 3.11 Motor Specification Sheet
3.3 Motor Controller Selection

An H-bridge motor controller was required to control the speed and the direction of the motors. The microcontroller would provide the necessary speed and direction control input to the motor controller using PWM. From the power requirement calculations in the earlier section, it was clear that the controller would have to be able to supply at least 17.55 watts of power to be able to achieve the speed and torque specifications. Also, from the motor specification sheet, it was noted that the stall current of the motor was 17A. Motor stall condition was a possibility that could not be ignored during controller selection. This meant that the selected controller would have to be able to supply a current of up to 17A if and when required (near motor stall condition). Further, the controller supply voltage had to be within the operating voltage of motors (3VDC-9VDC). If a single controller was to be used to control both the motors, the power and current ratings would have to be doubled.

Under these constraints, the Parallax HB-25 controller was chosen. It could supply 25A of constant current and 35A peak current at 13.8V, which was well above the motor stall current
of 17A. Further, its operating voltage range was 6VDC – 16VDC, which meant that it would be able to drive the motor at 9VDC. Although the power and current ratings of the controller were adequate to power two motors, the controller was designed to be used with a single motor (it had a single control output channel). Hence, it was decided to go with separate HB-25 controllers – one for each motor.

The detailed specifications of the HB-25 controller are given below.
3.4 Selection of Navigation Strategy

3.4.1 Motivation

The navigation strategy used in a mobile robot almost single-handedly influences the selection of sensors. Hence, before approaching the topic of sensor selection, the selection of navigation strategy has to be discussed. As explained earlier in the problem statement, it was decided that the initial strategy of the robot would be to patrol the perimeter of the area. As the robot was expected to be fully autonomous and its design and functioning required to be site-nonspecific, map based navigation was ruled out. Hence, wall following was chosen as the means of navigation and locomotion. Although this was not a very intelligent strategy, it had the advantages of being robust, site-nonspecific and was considered adequate for the purpose of perimeter patrolling. Furthermore, due to the nature of wall following based control, complex issues such as odometry, path planning and trajectory tracking were made redundant. This simplified the control implementation vastly.

While it performed its primary task of dispensing repellent stimuli, the robot would have three secondary tasks related to locomotion and navigation. These listed in the order of priority were:

a. Avoid ditches, which were defined as areas with sudden drops. E.g. stairs

b. Avoid obstacles, which were defined as areas with sudden increases in height. These may manifest themselves as objects like chairs, storage racks, waste bins etc, or even subtle elevations in the surface like raised floors.

c. Follow wall.
If ditches are encountered, the robot would follow the periphery of the ditch till wall is encountered. If a wall wasn’t encountered or was lost at any stage, the robot was to execute the wall finding algorithm. The wall finding algorithm consisted of moving outward along a circular path with steadily increasing radius, which would eventually degenerate into a straight line path. This is achieved in the following manner.

The velocity of the right wheel is kept constant ($V_R = V = \text{constant}$). Velocity of the left wheel follows the function given by,

$$V_L = V + aV \left(1 - \frac{x(t)}{b}\right)$$

Where $X(t)$ is a ramp function and ‘$a$’ and ‘$b$’ are weight constants whose values will determine the ‘tightness’ of the spiral path.

### 3.4.2 Wall Following Algorithm

The wall-following algorithm used to develop the code is explained in this section. As opposed to a control law which maintains a preset distance between the wall and the robot, a bang-bang controller (also known as on-off controller because it has no values in between) was used. If the distance between the robot and the wall was less than a certain set-point, the robot veered away from the wall. On the other hand, if the distance was more than the set-point, it would veer towards the wall. Thus the motion of the robot following a straight wall would look something like the image below.
If the robot was too close to the wall (as determined by another set-point with a lesser value), it would veer away sharply. Similarly, if the robot was too far from the wall, it would veer sharply towards the wall. This allowed the robot to go around sharp corners as illustrated in the figure below.

There were two types of corners that the robot would encounter – ones like those shown in case (a), where the adjoining wall was in the path of the robot, and ones like those shown in case (b), where the adjoining wall was not in the path of the robot. The green triangle
represents the robot, the solid black lines represent the walls and the dotted red lines represent the path of the robot.

If the second wall was in the path of the robot (case a), it would cause the distance sensor to give a lesser reading causing a state change and prompting the robot to veer away from the wall. If the rate of turning left wasn’t fast enough, there would be yet another state change causing the robot to veer faster. If the second wall was not in the path of the robot (case b), the wall sensor would give a higher reading, prompting the robot to veer right. The rate of turn would again depend on the state triggered by the distance reading. The robot would keep turning right till it encounters the wall and resumes normal wall following. Case (c) can be viewed as two consecutive instances of case (b), but the algorithm required to maintain wall-following for case (c) was slightly different. The third case required a separate state that carried a higher turn rate, which enabled the robot to complete the ‘U-turn’ and resume wall following. In the absence of this additional state, the robot would not be able to negotiate the sharp corner and follow the blue dotted path. It would subsequently lose the wall and commence the ‘wall-finding’ routine.

It must be noted that each state was associated with a set of velocity values for the left and right motor. Hence, a state change was equivalent to a step input for the motors. This step input was regulated in a PID closed loop. The flowchart of the algorithm is given below.
Figure 3.17 Wall-Following Algorithm Flowchart
### 3.5 Sensor Selection and Placement

The wall following algorithm detailed in the previous section could be implemented using a single, strategically placed, IR distance sensor. The placement of the IR sensor on the platform was critical for the bang-bang control to succeed. If the sensor was too far back on the robot, i.e., directly over the axle line and pointed straight at the side wall, implementation of this algorithm would fail. If the robot turned towards the wall, the sensor would show a longer distance, and the robot turned more, until it ran into the wall. (23).

![Incorrect Sensor Placement](image)

Figure 3.18 Incorrect Sensor Placement

However, if the sensor was mounted such that it fired at the wall at an angle, as shown in the figure below, the algorithm would work. If the robot turned towards the wall, the sensor would show a shorter distance and the algorithm would turn the robot away from the wall. Hence the wall following sensor was placed on the leading edge of the robot such that the IR beam made an angle of 45 degrees with the wall.
The wall following sensor was mounted on the second level mounting plate and was by design, the highest point of the robot. This was done to ensure that the sensor does not miss any obstacle that could go on to hit other components on the robot.
Although the wall-following algorithm required only one sensor for its implementation, the robot had two additional tasks of obstacle avoidance and ditch avoidance. These tasks needed sensors that could fire down as well as ahead of the robot. This problem was solved by mounting the sensor at an angle. This allowed the sensor to ‘look’ down as well as ahead. The figure below shows how ‘ditch detection’ and ‘obstacle detection’ was achieved using an angled sensor.

![Diagram showing how 'ditch detection' and 'obstacle detection' was achieved using an angled sensor.](image)

**Figure 3.21 Down-firing three Sensor Array**

Three such sensors were placed around the periphery of the robot on the second level, separated by 45 degrees each, as shown in the figure above. These sensors were mounted on the second level so that the floor was within the detection range. If the sensors were mounted on the first level (on the chassis), the distance to the floor would have been out of range on the
lower side. This would have given erratic floor height readings. These three sensors would look out for obstacles and ditches on the ground as the fourth sensor was used for wall following.

![Diagram of obstacle detection and ditch detection with angled sensor](image)

*Figure 3.22 Ditch detection and obstacle detection with angled sensor*

IR distance sensor was a clear choice. Laser sensors were too expensive and sophisticated for the application. Ultrasonic SONAR sensors could have been used. However, one of the repellent stimuli was ultrasonic vocalisation, which could have interfered with the operation of the SONAR sensor. Hence the SONAR sensors were avoided. Other advantages of using IR sensors were they were inexpensive (about 1/4 the price of Ultrasonic sensors), they were highly tolerant of ambient light and IR interference and were nearly immune to variations in object colour and reflectivity.
Another design decision was to ensure that the IR sensors could provide distance data using serial output. This ensured that the distance output was digital and hence not susceptible to noise like its analog counterpart. This also meant that a microcontroller without analog-to-digital converters could be chosen.

It should be noted that the wall following algorithm detailed in the earlier section could have been implemented using only proximity sensors. However, any change to the set-points would have required actual physical adjustment of the proximity sensor. Furthermore, each additional case would have required an additional proximity sensor, which would have complicated the system.

Hence, an IR distance sensor with a range of 100mm to 800mm with 8-bit serial output (model DIRRS+) by Solarbotics Corporation was selected. The specification sheet of the sensor is given below.

Figure 3.23 IR Sensor - DIRRS+
Since the wall-following application did not demand precise odometry, the use of the encoder was restricted to closing the PID loop around the step inputs generated by state change. Hence, the encoder did not have to be very precise. Few restrictions on the selection of the encoder included TTL output and hub diameter of 10 mm. The encoder was to be mounted onto the gearbox of the gear motor in the ‘through-hole’ style.

The E2 series Koyo encoder with a resolution of 500 pulses per revolution was selected. This would provide an accuracy of ±0.45 mm which was considered adequate for the application.
3.7 Repellence Stimuli Selection

3.7.1 Strobe Selection

Selection criteria for a strobe light were high flash rate (≥ 60 flashes/minute) and 12 VDC operating voltage. Accordingly a xenon tube flashing strobe of ‘Velleman’ make, with a flashing rate of 100 per minute and an operating voltage of 12 VDC was selected.

![Velleman Strobe](image)

Figure 3.26 Velleman Strobe

3.7.2 Ultrasonic Playback Setup Selection

The highest frequency that was to be reproduced in the stimulus signal was around 22 kHz. According to the Nyquist Sampling Theorem (13), the minimum sampling frequency (Nyquist Frequency) had to be 44 kHz, which was very close to one of the industry standard sampling rates of 44.1 kHz. However, in practice, the sampling frequency is always significantly higher than the Nyquist frequency. Hence, the next standard frequency of 48 kHz was selected. Thus, the playback setup had to be able to play audio files (in .mp3 or .wav format) with a sampling rate of 48 kHz, with a frequency response that extended at least up to 25 kHz. Any commercial
embedded audio chip could perform the operations of data retrieval from the audio file and digital-to-analog conversion at 48 kHz. However, the amplification and the playback with ultrasonic frequency response were not possible with generic audio amplifiers and speakers. Most audio amplifiers and speakers are designed for a frequency response of 20 Hz – 20 kHz. Hence audio reproduction in the ultrasonic range demanded special purpose ultrasonic amplifier and transducer. This had already narrowed the selection. However, an additional constraint on the amplifier-transducer package was the ability to operate on 12 VDC. These specifications were met by a single supplier, ‘MySkunkWorks’. Their ultrasonic amplifier had a frequency response that extended up to 30 kHz and could run on 12 VDC. The uMP3 embedded mp3 player chip was used as the playback module.

The mp3 playback module, ultrasonic amplifier and the transducer are shown below.
Figure 3.27 Rogue Robotics mp3 playback module

Figure 3.28 Ultrasonic Amplifier

Figure 3.29 Ultrasonic Transducer
3.8 Battery Pack Selection

The battery pack was selected based on the voltage and current requirement specifications of the application. These specifications included:

   a. Operation Voltage (V)
   b. Capacity (A-h)
   c. Discharge Rate (A)
   d. Desired Run-time

Secondary selection criteria included overall dimensions, weight, cycle life, etc.

In order to calculate the required battery capacity, the total current consumption was determined. This was the sum of the current consumption of individual components. The consumption data was obtained from the component data-sheets. The following table shows the current consumption of individual components in the robot and the total expected current consumption.

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Component</th>
<th>Units</th>
<th>Consumption (mA)</th>
<th>Total Consumption (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motor</td>
<td>2</td>
<td>1900</td>
<td>3800</td>
</tr>
<tr>
<td>2</td>
<td>Rabbit Microcontroller</td>
<td>1</td>
<td>325</td>
<td>325</td>
</tr>
<tr>
<td>3</td>
<td>MP3 Module</td>
<td>1</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>Motor Controller</td>
<td>2</td>
<td>80</td>
<td>160</td>
</tr>
<tr>
<td>5</td>
<td>Encoder</td>
<td>2</td>
<td>88</td>
<td>176</td>
</tr>
<tr>
<td>6</td>
<td>IR Sensors</td>
<td>4</td>
<td>35</td>
<td>140</td>
</tr>
<tr>
<td>7</td>
<td>TTL Converter</td>
<td>1</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>8</td>
<td>Strobe Light</td>
<td>1</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>9</td>
<td>Amplifier</td>
<td>1</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>10</td>
<td>Speaker</td>
<td>1</td>
<td>1414.2</td>
<td>1414.2</td>
</tr>
<tr>
<td></td>
<td><strong>Total Consumption</strong></td>
<td></td>
<td></td>
<td><strong>9220.2</strong></td>
</tr>
</tbody>
</table>
Thus, total current consumption of the robot in operation is 9.22 amperes. The battery capacity is simply the total current consumption times the desired runtime. Since this is a ‘proof of concept’ prototype, a runtime of 1 hour was deemed adequate. Thus the battery capacity would have to be at least 9.22 A-h.

The discharge rate of a battery is the maximum amount of current it could supply during its operation. If a battery was rated with a capacity of ‘x’ A-h, it did not necessarily follow that it could deliver ‘x’ amperes for 1 hour. On the other hand, the battery could deliver ‘2x’ or even ‘3x’ amperes for 30 minutes or 20 minutes respectively. Hence, it was important to know the discharge rating for a battery, as it determined the amount of current available to tap. As per the table shown above, the total current drawn by the robot was 9.22 A. However, the motor stall current was rated at 17A. Hence in the worst case scenario, with both motors in near-stall conditions, the battery would have to supply 34 A. Hence, the discharge rate specification for the application was 34 A and not 9.22A.

With the above specifications in mind, a customized Lithium-ion Phosphate battery pack from ‘Batteryspace Inc.’ was chosen. Its specifications were,

a. Operation Voltage (V) = 12.8 V
b. Capacity (A-h) = 12.8 A-h
c. Discharge Rate (A) = 40 A
d. Expected Run-time = 1.3 hours.
Additionally, it had built-in electronic protection for overcharge, over-drain, over-discharge and short-circuit. It also came with its customized charger. The battery pack and the charger unit are shown below.

![Battery Pack and Charger](image)

**Figure 3.30 Battery Pack and Charger**

3.9 **Selection of Stimuli and test protocol**

After reviewing various repellence mechanisms, it was decided that alarm signals in the form of low-frequency (22 kHz) ultrasonic vocalizations combined with a 2 Hz strobe would be used as repellent stimuli. Each of these would have random duty cycles (ON times and OFF times) which would be regulated by the microcontroller.

This concludes the design of the mobile rodent repellent robot.
Figure 3.31 Final Assembly – Front View
Figure 3.32 Final Assembly - Isometric
4 Conclusion

What was achieved?

The proposed mobile rodent repellent robot was successfully designed and built. The repellent stimuli were identified and an integrated repellence strategy was formulated. This included ultrasonic audio stimuli and visual stimuli.

The navigational abilities of the robot were extensively tested. The robot was able to follow walls around acute and obtuse corners. It was also able to follow objects that were lined along the wall, like trash cans, tables, desks, bookshelves and even irregularly shaped objects like filled garbage bags. The robot showed good robustness in detecting and circumventing random obstacles in its path, and in detecting and following the edge of staircases.

Hence, it can be concluded that the navigational performance of the robot meets the specifications outlined in the problem statement.

What could not be achieved?

The efficacy of repellence with live rodents could not be tested in a controlled laboratory setting. Animal testing was a totally foreign area. Hence, contacts and information regarding infrastructure, procedures and protocol was very hard to come by. Over time contacts were established through networking and research. When the collaboration was discussed with these contacts, it was realised that testing on live animals would require the approval of the University Animal Care Committee (UACC) at the University of Toronto. The next meeting of the
UACC was scheduled for Fall 2011, which was after the completion deadline for this project. Hence, the repellence could not be tested for its efficacy.

**Direction for future work**

Several avenues can be explored in the future on this project:

- Repellence efficacy testing can be carried out with live rodents. Results of the tests should be used to tune the repellence strategy with respect to parameters like strobe duty cycle, USV duty cycle, USV amplitude, etc.

- The use of chemical stimuli (irritants like capsaicin and semio-chemical mimicry agents like synthetic predator odours can be explored)

- A more sophisticated strategy navigation strategy that combines elements of SLAM with wall following can be explored.

- Similarly, the feasibility of a more active repellence strategy, where the robot will attempt to locate rodents rather than passively patrol the perimeter, can be explored. The possibility of using thermal imaging to isolate the heat signature of a rodent can be explored.
5 Bibliography


3. Frightening Methods and Devices/Stimuli to Prevent Mammal Damage - A Review. Ann E.


6. Responses of Confined Rodent Populations to an Ultrasound Generator. J. H. Greaves, F. P.

7. Variables Affecting Ultrasound Repellency in Philippine Rats. S. A. Shumake, et al. 1, 1982,


#5-40
2 Tapped holes

(.750) (1.000)

(.230)

\( \Phi 0.500 \)

\( \Phi 0.375 \)

Qty: 2

Shaft Coupling 2D

RAL-MRR-02
Caster Mounting 2D

Qty: 1

RAL-MRR-03
Qty: 5

Stack Support

RAL-MRR-05

Black Anodised

Material: Aluminium

Dimensions are in millimeters:
- Length: 76 mm
- Diameter: 5 mm
- Both ends tapped 10mm Ø
M2.5 Tapped
4 Holes on
φ75 P.C.D

φ0.20
4 Holes

φ0.40
0.12
4 Holes

SECTION C-C

Encoder Mounting
RAL-MRR-12

Qty: 2
Appendix B – Schematic Circuit Diagram