LOVOTICS: LOVE + ROBOTICS, SENTIMENTAL ROBOT WITH AFFECTIVE ARTIFICIAL INTELLIGENCE

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2011

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A THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

NATIONAL UNIVERSITY OF SINGAPORE

NUS Graduate School for
Integrative Sciences and Engineering

2011

Abstract

Lovotics refers to the research of human - robot relationship. The general idea of Lovotics is to develop a robotic system which strives to achieve a high level of attachment between humans and robot by exploring human love. Such relationship is a contingent process of attraction, affection, and attachment from humans towards robots and the belief of the vice versa from robots to humans.
The first step in Lovotics is to develop a deep understanding of the physics, physiology, and emotions of the human being in order to model this in the robot. Even though various fields have proposed ideas about the role and function of love, the current understanding about love is still quite limited. Furthermore, developing an affection system similar to that of the human being presents considerable technological challenges.
A robot was designed and developed using several design theories for the hardware and various novel algorithms for the software. The artificial intelligence of the robot employs probabilistic mathematical models for the formulation of love. An artificial endocrine system is implemented in the robot by imitating human endocrine functionalities. Thus, the robot has the capability of experiencing complex and human-like biological and emotional states as governed by the artificial hormones within its system. The robot goes through various affective states during the interaction with the user. It also builds a database of interacting users and keeps the record of the previous interactions and degree of love.
The novel advanced artificial intelligence system of Lovotics includes an Artificial Endocrine System (AES), based on physiology of love, Probabilistic Love Assembly (PLA), based on psychology of love, and Affective State Transition (AST), based on emotions, modules.
Psychological unit of the Lovotics artificial intelligence calculates probabilistic parameters of love between humans and the robot. Various parameters such as proximity, propinquity, repeated exposure, similarity, desirability, attachment, reciprocal liking, satisfaction, privacy, chronemics, attraction, form, and mirroring are taken into consideration.
Physiological unit of the Lovotics artificial intelligence employs artificial en-

docrine system consisting of artificial emotional and biological hormones. Artificial emotional hormones include Dopamine, Serotonin, Endorphin, and Oxytocin. For biological hormones Melatonin, Norepinephrine, Epinephrine, Orexin, Ghrelin, and Leptin hormones are employed which modulate biological parameters such as blood glucose, body temperature and appetite.

A wealth of information about a persons emotions and state of mind can be drawn from facial expressions, voice, gesture, etc. The affective system of the robot analyzes system inputs to generate suitable states and behaviors for the robot in real-time. The affective system is modeled as closely to the human being as possible in order to be an emotionally engaging system.

The robot is an active participant in the communication process and adjusts its internal affective states depending on inputs and feedback from the human.

Based on love measurement methods for humans, a novel method for measuring human - robot love is proposed. This method is employed in order to evaluate the performance of Lovotics robot.

Two possible further applications of Lovotics of Lovotics are also proposed, which are kissing transfer system and leader robots. Also ethical issues of Lovotics are also discussed.

Lovotics is as multidisciplinary research field utilizing fundamental concepts from philosophy, psychology, biology, anthropology, neuroscience, social science, engineering, robotics, computer science, and artificial intelligence.

Proposed engineering approach provides a system consisting of relevant modules allowing the development of functionalities based on multidisciplinary research yielding a new form of love relationships between robots and humans.

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Dedication

To:
My Parents, Behrouz Samani and Mahnaz Zamani;
and my brother Pouya.

Acknowledgment

I would like to thank all those who strongly supported me during my PhD:

PhD supervisor and member of Thesis Advisory Committee, Prof. Adrian D. Cheok;

Thesis Advisory Committee Chair, Prof. Hang Chang Chieh;

Thesis Advisory Committee Member, Dr. Tim Marsh;

PhD Thesis Examiners;

National University of Singapore and Keio University of Japan Professors, especially, Prof. Shuzhi Sam Ge, Prof. Masa Inakage, Prof. Okude Naohito, Prof. Tham Ming Po, A/Prof. Annett Schirmer, A/Prof. Henry Duh, A/Prof. Shen Zhao, A/Prof. Lonce Wyse, Dr. Hideaki Nii, and Dr. Ajith Madurapperuma;

Undergraduate students of Department of Electrical and Computer Engineering, NUS, who worked with me on Lovotics project as they Final Year Project (FYP); Lian Yuanlin, Deng Ding Yun, Arjun Nagpal, Foo Wui Ngiap, Qiu Mingde, and Ying Hao Janus Ong;

Research Fellows, Reseach Engineers, Interns, Designers, and Programmers who collaborated with me in different aspects of my thesis;

My PhD scholarship, NGS, management board and staffs;

Members of Electrical and Computer Engineering Department and Interactive and Digital Media Institute in Keio-NUS CUTE Center and Social Robotics Lab, National University of Singapore: Elham Saadatian, Newton Fernando, Mili Tharakan, Jeffrey Koh, Doros Polydoru, Angie Chen, Kewpie Wu, James Teh, Roshan Peiris, Ken Zhu, Yan Yan Cao, Yongsoon Choi, Nimesha Ranasinghe, Dilrukshi Abeyrathna, Jun Wei, Wang Xuan, Kasun Karunanayaka, Isuru Godage, Michelle Narangoda, Shigueo Nomura, Eng Tat Khoo, Tim Merritt, Rosalie Hsu, Norikazu Mitani, Sudarshan Balachandran, Aswin Thomas, Bahareh Ghotbi, Yaozhang Pan, Pey Yuen Tao, and Brice Rebsamen;

My family and friends.

Chapter 1

Introduction

1.1 Lovotics interpretation

Definition of love between humans and robots can be analogous with the one between humans. With the purpose of defining love for Lovotics, the most prominent manifestations of love within philosophy, literature, and psychology are investigated to find the element of resemblance in order to map that to a human - robot love definition.
The concept of love is extremely mysterious and enigmatic but at the same time it is highly inebriating and intoxicating. Various proposed interpretations of love generally have the contingent nature which causes several debates and critics for any suggested elucidation.
Through out history there are several cases that looked at the structure of the love as a process.

1.1.1 Human - human love

Comprehension and explanation of the concept of love has been a challenging dilemma for human beings.
Ancient Greeks used few distinct words for love which Eros, Philia and Agape are the most renowned ones [224]. In Plato's Symposium [195] ``Eros´´ is used to refer to that part of love constituting a passionate and intense desire. The Platonic-Socratic position maintains that the love we generate for beauty can never be truly satisfied until we die. ``Philia´´ is a dispassionate virtuous love which in Aristotle's book, The Nicomachean Ethics [9], is usually translated as friendship. According to Plato's ladder model of love, a lover progresses from rung to rung from the basest love to the pure form of love. ``Agape´´ generally refers to a perfect kind of love without the necessity of reciprocity [224].

The Persian word for love is ``Eshgh´´. Seven Valleys of Love (Haft Shahre Eshgh) are stated in the Manteq al-Tayr [14] by Attar, a Persian poet and theoretician of Sufism, as quest, love, understanding, independence and detachment, unity, astonishment and bewilderment and finally deprivation and death.
The term ``Courtly Love´´ was introduced by French medievalist, Gaston Paris, in 1883 as ``amour courtois´´ [184]. Inherent nature of courtly love is an experience between erotic desire and spiritual attainment. The following stages of courtly love were identified by Barbara Tuchman from her studies of medieval literature [234]: Attraction to the lady, usually via eyes/glance; Worship of the lady from afar; Declaration of passionate devotion; Virtuous rejection by the lady; Renewed wooing with oaths of virtue and eternal fealty; Moans of approaching death from unsatisfied desire (and other physical manifestations of lovesickness); Heroic deeds of valor which win the lady's heart; Consummation of the secret love; Endless adventures and subterfuges avoiding detection.
The themes of Courtly Love were not confined to the medieval. Shakespeare's Romeo and Juliet [219], for example, shows Romeo attempting to love Rosaline in an almost contrived courtly fashion while Mercutio mocks him for it.
In a science fiction story by Isaac Asimov, ``True Love´´ [13], the person who is trying to find his ideal match with employing a special computer program (Joe), which has access to databases covering the entire populace of the world, realizes that looks alone are not enough to find an ideal match. In order to correlate personalities, he speaks at great length to Joe, gradually filling Joe's databanks with information about his personality.
In ``Great Expectations´´, a novel by Charles Dickens [57], story of a man or woman in their quest for maturity, usually starting from childhood and ending in the main character's eventual adulthood basically illustrates the process of life attempt to become mature along the way.
In what Freud calls ``The development of the ego´´ [83] the child moves towards a fuller recognition of those who care for him as independent beings and develops his affection to them [59].
Irvin Singer in the book ``The nature of love´´ [222] claims that each variety of love, involving its special object, has its own phenomenology and iridescence within the spectrum that delimits human experience.
Psychologist and social philosopher, Erich Fromm, in his book ``The art of loving´´ [86] describes love as a skill that can be taught practiced and developed. He compares the practice of love with the practice of other arts. He believes that to reach the personal qualities for ability to love learning and time is essential. On the other side, Ilham Dilman in his book ``Love: its forms, dimensions and paradoxes´´ [59] does not see love as practice but however argues that love is active or passive engagement with another person. He believes these engagements to belong to and being part of individual's life.

Above interpretations of love are some of the most renowned cases which as it is apparent are contrastive in many aspects. However a continuum and process is observable in the nature of all.

1.1.2 Human - robot love

Love is unpredictable and a great mystery which no one has manage to decipher. Definition of love is absolutely controversial. However, as mentioned above, in several theories of human love, it has been seen as a ``process'' between two parties in most of the definitions throughout history. Lovotics is inspired from human love; hence human - robot love in Lovotics also assumed to be a process. John Brentliger in the book chapter ``The Nature of Love'' in Alan Soble's book, ``Eros, agape, and philia: readings in the philosophy of love'' [224] declares that following Plato, most of the philosophers of love have mainly discussed four issue in this regard: Object of love, sort of state, desire, and valuation. These four issues can be discussed for human - robot love as well.
Even though there is much discussion for defining object of love in human love but in Lovotics clearly object of love is the human. The main target of Lovotics is happiness for human beings with employing a robot to generate that feeling. Second issue is to find whether love in Lovotics is a sensation, an emotion, a belief or something else. Many robots are equipped with state of the art emotion recognition and expression systems. Nowadays robots are capable of showing realistic gestures, postures and expressions by employing advances in robot design and development. On the other side, affective computing researchers propose several methods to capture and understand emotions during interaction with high degree of accuracy. In spite of the fact that advances in emotional expressions and analysis would help to develop competent physical demonstrations of feeling but love itself cannot be considered as emotion essentially. We may need to employ another mechanisms in robots inspiring from the nature of love in humans.
Third issue is the relationship between love and desire in Lovotics. The main question is whether to assume desires to be egocentric or not. Programmability of robots also can be employed in order to reinforce the relationship towards benefiting human beings.
Connection between valuing and loving is the fourth issue of Lovotics. Humans may value robots when loving them but there is question whether they love robots in the case that they value them. Intrinsic valuation can be considered in human - robot relationship for further clarification.
When reciprocated love becomes a relationship [158]. The reciprocation between human and robot can happen through the interaction. ``Human to robot (human → robot)'' love refers to the fact that human loves a robot, but regarding ``robot to human (robot → human)'' love, Lovotics definition is that the human

believes that he/she is being loved by a robot. Consequent four dimensions of this bi-directional love are: Robots express love to humans; Robots receive and comprehend love from humans; Humans love robots and finally humans believe that robots love them. Thus we assume humans to be the center of the Lovotics and robots' love are only admissible when felt by humans.
In order to provide a (quasi) definition of love for Lovotics, recent practical based studies of love should be considered.
The psychologist, Robert Sternberg, in the book ``Cupid's arrow: the course of love through time´´ [227] introduces the triangle of love consist of intimacy, passion and commitment that may be present is various degrees in a relationship. Regarding passion Sternberg draws on Elaine Hatfield's and Richard Rapson's definition of passionate love [112, 110] as a strong desire for union with another person as complex functional whole including patterned psychological process. Helen Fisher proposed that humanity has evolved three core brain systems for mating and reproduction: lust (the sex drive), attraction (early stage intense romantic love) and attachment (deep feelings of union with a long term partner). She claims that love can start off with any of these three feeling [76].
Accordingly three parameters of attraction, affection, and attachment are also employed in proposed definition of love for Lovotics. Attraction mostly refers to the physical aspects of love which can be related mostly to the design of the robot. Affection is related to intimacy to develop a deep emotional connection between robots and humans. Attachment refers to long term bond between humans and robots. These three parameters are not essentially in order. For example one may be attracted to a robot because of its cute design or one can spend lots of time with a robot initially and feel positively towards the robot afterwards.

1.1.3 Definition of love for Lovotics

Based on the above discussed issues we define love in Lovotics as:

> ``**Love in Lovotics (Human - Robot Love) is a contingent process of attraction, affection and attachment from humans towards robots and the belief of vice versa from robots to humans**.´´

Of course the proposed definition should be considered as an initial interpretation for human - robot love. One might argue that proposing an exact definition (even for human love) is not essential but by having a clear (and even primary) definition, a clear idea for the design and development of the software and hardware would be more practical for robotics researchers.
The general motivation for Lovotics research is simply providing happiness for

humans with the hope to improve affective qualities of humans daily life.

1.2 Lovotics system structure

The overall system structure of Lovotics robot is presented in Figure 1.1. The system consists mainly of four input modules, which captures basic sensory data such as sound, vision, touch and acceleration. A Separate pre-processing algorithm is designated for each input, as the raw data needs to be prepared before being sent to the artificial intelligence module which compute the love probability, hormonal levels, and affective states of the robot.
The output generator is a separate layer which maps the internal state of the robot towards rational behavior. Lastly, various behavioral patterns of the robot is represented using outputs generated by audio devices, motion devices and illumination devices.

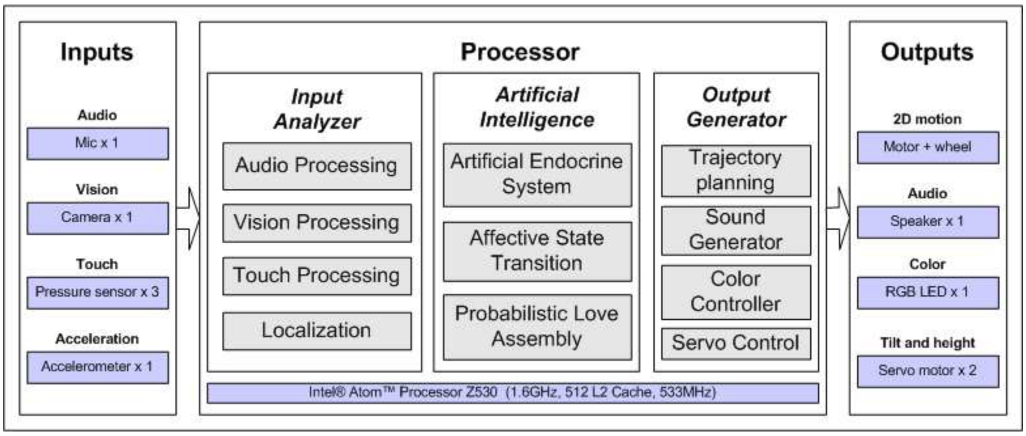

Figure 1.1: The overall structure of Lovotics robot which was developed in the research. Dark color boxes indicate hardware and light color boxes indicate software.

1.2.1 Inputs

Audio, touch, and vision are the main input channels of interaction for the Lovotics robot. Furthermore, accelerometer data is used for the purpose of localization and navigation. Lovotics robot perceives the information about interacting environment by means of these input channels. These inputs from these sensors are processed accordingly to generate the affective system.

1.2.1.1 Audio

A wealth of information about a person's emotions and state of mind can be drawn from an audio input. The audio input perceived by the audio input module of the system will be fed into the audio processing module where the relevant audio parameters will be extracted to provide required parameters for the artificial intelligence module.

1.2.1.2 Vision

Facial analysis is one of the key parameters for emotion recognition in human - robot interaction. Visual system of Lovotics is capable of detecting, tracking and recognizing facial images, as well as analyzing the facial expressions. The system has been designed to capture facial information, by simulating the human task of searching one's vision space for familiar faces, and then focusing on a face of interest to interpret his emotions and behaviors.

1.2.1.3 Touch

Touch plays a key role in establishing intimacy or affection in interpersonal relationships. It not only provides a way of interacting with the user but also describes the proximity of the user with respect to another user or robot. In this system, touch is used as one of the inputs to identify the proximity of the user. Based on the place, area and pressure of touch, different behaviors of the robot are defined.

1.2.2 Process/Artificial intelligence

The processing unit of the Lovotics robot consists of input analyzer, artificial intelligence and output generator.
The input analyzer module is in charge of processing sensory inputs and output generator module produces various behaviors of the robot by controlling servo motors, RGB LEDs, robot's audio output, and trajectory planning of the robot. Artificial intelligence (AI) of Lovotics consists of three modules:

- The **Probabilistic Love Assembly (PLA)** module is used to calculate probabilistic parameters of love between a human and a robot. Various parameters such as proximity, propinquity, repeated exposure, similarity, desirability, attachment, reciprocal liking, satisfaction, privacy, chronemics, attraction, form, and mirroring are taken into consideration.

- The **Artificial Endocrine System (AES)** of Lovotics resembles the human endocrine system and translates it to the robot through artificial hormones. As hormonal state of the robot, levels of these artificial hormones change dynamically due to interactions and situational awareness.
- The **Affective State Transition (AST)** module is proposed which could be employed to manage alteration of the short-term affective states of the robot.

1.2.3 Outputs

The state and emotions of the robot are expressed to interacting humans by means of outputs. Although, there are several behaviors such as navigation, color change, tilt and height that the robot can display; audio output plays major part in inducing/encouraging the bi-directional human - robot relationship for Lovotics. A sound engine was implemented to allow for synthesizing of real-time affective sounds that could be driven by outputs from the AI module, thus creating sounds that are responsive to the user's emotions and enhanced the positive interaction feelings between the humans and the robot.
The Lovotis robot is shown during interaction in Figure 1.2.

Figure 1.2: Lovotics robot during interaction.

The main contributions of this thesis are as follows:

- The concept of Lovotics is structured in the academic format.
- Philosophy of Lovotics is illustrated.
- Multidisciplinary approach is employed for development of Lovotics modules.
- A robot according to abstract design philosophy is developed.
- Multimodal sensor - processor - actuator system is integrated.
- A novel affective artificial intelligence of Lovotics is designed and developed which includes, Probabilistic Love Assembly, Artificial Endocrine System, and Affective State Transition modules.
- Evaluation method of human robot love is designed and employed to investigate the performance of the developed robot.
- Fundamental structure for future research of Lovotics is generated to pave the way for future applications.

Chapter 2

Literature Review

2.1 Related works

Following the advent of industrial, service, and social robots, Lovotics introduces a new generation of robots, possessing the ability to love and be loved by humans. Numerous works have been done in the field of robotics, ranging from industrial to interactive and social robots. By emphasizing on assimilating robots into human society, many conceptual as well as hypothetical parameters were taken into consideration while adhering to Asimov´s laws of robotics [12]. The human - robot interaction in social and interactive robots has been studied extensively by researchers like Murphy [171, 170], Ishiguro [117, 133], Breazeal [38], and Goodrich [95, 96]. Although the field of social robotics is advancing prominently, development of human - robot interaction at an interpersonal level is still left with a wide scope for research and development.

An industrial robot is an automated and programmable robot with sufficient dexterity to be largely used for manufacturing purposes. Some of the important applications of industrial robots include welding, painting, assembly, pick and place, packaging and palletizing, product inspection, and testing, all accomplished with high endurance, speed, and precision [257]. The movement and applications of the industrial robots are based on various parameters like speed, accuracy, degree of freedom, and kinematics [249]. One of the most popular applications of industrial robots are heavy duty robotic arms [255] which use complex industrial robot programming techniques [6] for accurate and speedy pick and place tasks.

Service robots assist human beings by carrying out undesirable tasks typically considered dirty or dangerous. They are usually operated by a built-in control system, with manual override options [4]. Domestic robots like Roomba [127] and Cleanmate [69] are consumer robots [25], whereas, robots like PatrolBot

[118] and Desire [189] perform tasks like patrolling and trash tossing, respectively. Different applications of service robots are cleaning and housekeeping, edutainment, humanitarian demining, search and rescue, food industry, rehabilitation, inspection, agriculture and harvesting, lawn mowers, surveillance, medical applications, mining applications, construction, automatic refilling, guides and office, fire fighters, and picking and palletizing [136].

A social robot is an autonomous robot that interacts with humans by following the social rules attached to its role. Extensive researches carried out in the field of social robotics, have made them more human-like and user friendly. As an example, Leonardo [196] does not mimic any creature and has an organic appearance. Its behavior is supported by multi-axis controllers, sensate skin and a learning mechanism socially guided through intimation and human tutelage. Robots like Rocco [91] and Kismet [37] provide a great scope of development in the field of social robots.

Social acceptance of robots can be evaluated based on parameters like physical appearance, usability, and feedback. With the advancement in technology and increased number of researches in the field of robotics, the fine line between these parameters is vanishing. Saya [109], Asimo [202], and Geminoid [176] are examples of human-like robots (humanoids) which replicate human beings not only in appearance but also in their actions. One of the main intentions for developing these robots was to overlay the physical appearance and usability parameters, bringing them closer to human social levels.

Social and interactive robots are brought closer to personal levels of interaction through domestic robots like the PR-2 [89]. Personal level interaction is also established in recreational and pet robots. These robots are also for robotherapy and robopsychology where they establish emotional relationships with the elderly to encourage social interaction [138, 246]. Robotic pets such as AIBO [87] produce similar positive chemical responses in children by taking on the form of a puppy.

Purely therapeutic robots such as Paro [220] are currently in use in hospitals and in elderly nursing homes. Paro has been shown to decrease stress levels in elderly patients [247]. It also aided in patient/caregiver communications by providing a common point of positive interactions, and reduced feelings of burnout in the caregivers.

Probo [99] is a huggable social robot with 20 degrees of freedom for head movement which is developed as a research platform to study cognitive human-robot interaction with a special focus on children.

As a more advanced robot, Nexi [3] is introduced as Mobile/Dexterous/Social (MDS) type of robot. Nexi moves around on wheels (mobile), picks up objects (dexterous), and expresses a startling range of emotions (social).

Social robotics has attracted lots of researchers because of the amount of room

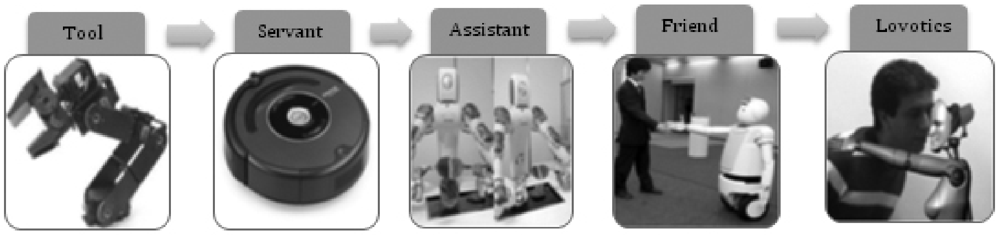

Figure 2.1: Transition from functional robots towards affective robot

available for further improvement and implementation. Every new research related to social robots brings forth a new design or technique for human - robot interaction. Several aspects of the social and interactive robots have been investigated by researchers. For example, Gockley [138] focused on designing methodology for long term interacting social robots, whereas Dautenhahn [51, 50] investigated the possibility of robots as human-like social actors which can mimic humans as closely as possible while possessing artificial social intelligence.

Human - robot relationship is an outcome of advanced level of human - robot interaction. The idea of romance between humanity and mechanical creations is not new. This notion has persisted for the past 40 years with students becoming attracted to ELIZA [253], a computer program designed to ask questions and mimic a psychotherapist.

The examples mentioned so far have shown the flexibility and variety of research aspects available in the field of human-robot relationships [52]. Research themes depend on two major factors of dependence (functional) and attachment (affective). The first factor defines the functionality and usage of the robot. The second factor takes into account the feelings and attachment of the user towards the robot. Based on the role of the robot in human - robot interaction, a diagram for various types of robots is presented in 2.1. A gradual shift from functional robots towards affective robots can also be seen.

Although most of the previous robots perform well in human-robot interaction environment, they are lacking in feedback mechanisms and experiential interactive behavior. To fill this void in human-robot relationship, Lovotics aims to develop the ability to establish human - robot bi-directional love.

Today, most of the robots are developed to solve some particular task or at least simplify it. The scope can vary from mundane tasks to complex processes. Relative feedback from the robots based on human - robot interaction plays a crucial role in bringing robots closer to the user. To analyze how robotic feedback effects human emotional attachment, six popular robots were chosen and a study was performed to understand their level of interaction. Based on the information

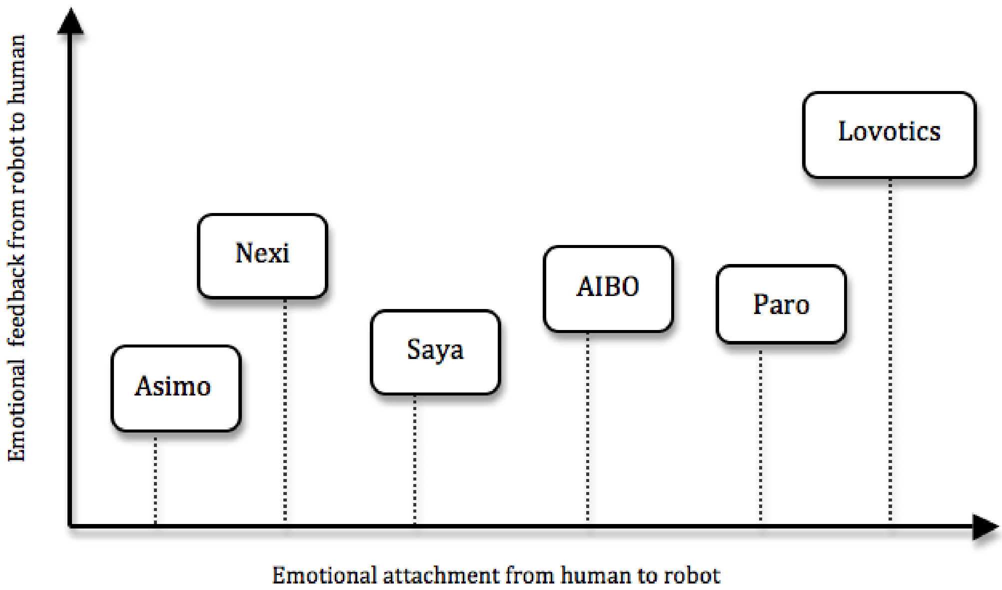

Figure 2.2: Comparison of robots based on feedback

Table 2.1: Comparison of Robots based on Features

Features	Asimo	Nexi	Saya	Aibo	Paro	Lovotics
Mobility	✓	✓	×	✓	×	✓
Sociability	✓	✓	✓	✓	✓	✓
Love	×	×	×	×	×	✓

gathered from available sources, a crude comparison chart was derived and illustrated in Figure 2.2.

An analysis of various popular robots in comparison with the Lovotics robot based on their features is given in Table 2.1. The Lovotics robot is proposed to be the only robot which has the ability to love and establish a bi-directional human-robot relationship.

The development of robots from abstract concept to humanoids goes through many phases of improvements. Unlike domestic robots such as Roomba and Aibo, robots like Enon [132] are closer to human beings in their physical appearance and resemblance. Humanoid robots like Saya, Asimo, and Geminoid possess the ability to express emotions and generate emotional responses from humans. However, the proposed version of Lovotics robot does not seek to mimic the physical form of humans, and is therefore, considered an abstract robot. In place of physical appearance, Lovotics aims to emulate humans in terms of emotion and behavior. Figure 2.3 represents the human resemblance scale of various robots.

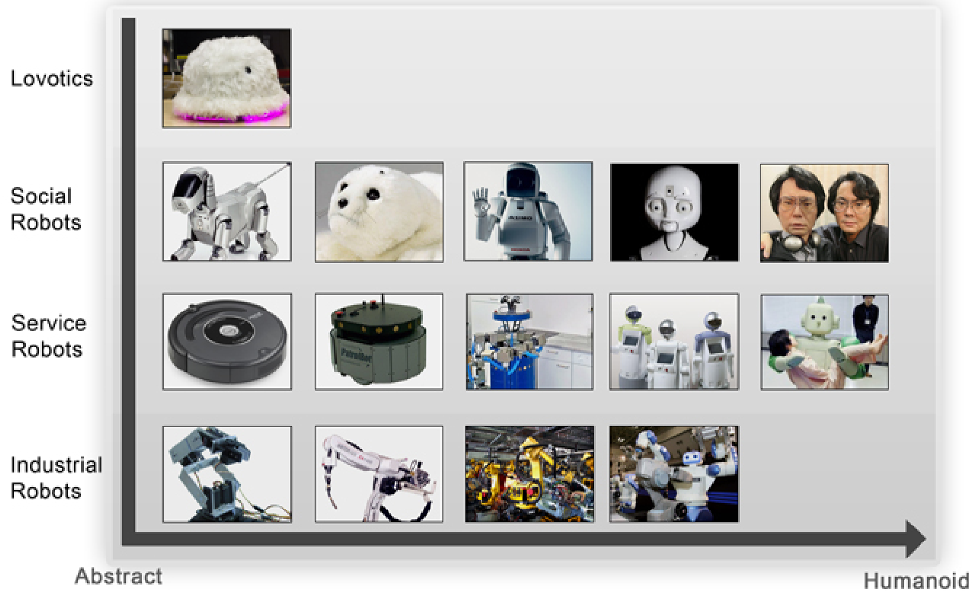

Figure 2.3: Human resemblance scale of various robots

2.2 Background

2.2.1 Lovotics modules

Relevant literature review for various modules of Lovotics is presented in this section.

2.2.1.1 Sensors

Audio A human voice becomes effectively potent and acquires the capacity to influence behavior simply based on the content of the words spoken by that voice on a previous occasion [28]. The complete process of vocal communication of emotion includes encoding (expression), transmission, and decoding (impression) of vocal emotion communication [213]. Some robots have the ability to have interactive spoken language dialogue with human [141, 153] and some just use specific audio features like pitch [181] without looking into the linguistic content [35, 36].
Audio recognition is a wide area of research comprising of processes like speaker recognition and voice recognition. From technological advancement in health

care or military equipment [85, 22] to bringing technologies closer to human, audio recognition stands firm in establishing a high-end human computer interaction environment. In voice recognition (often coined as speech recognition), audio inputs are passed through relevant filters and models to extract the required information [218]. The two most commonly used models are language model and acoustic model for Natural Language Processing (NLP) [102, 200, 129] and speech pattern recognition [216, 54]. Audio input can also be in non-speech form, which means, it can comprise of sequence of harmonics with varying pitch and loudness, thus providing it uniqueness. In such cases, non-dialogue based recognition is used by applying Mel Frequency Cepstral Coefficients (MFCC) [268]. Emotion recognition from audio is one such example. In some situations, instead of advanced MFCC algorithm, basic parameters like pitch and loudness are used for recognizing the emotions [125, 134].
It is also possible to recognize the speaker from the processed audio input. The speaker recognition process comprises of two major methodologies; speaker verification and speaker identification where $1:1$ and $1:N$ matching of audio input with available templates are performed, respectively [208, 203]. Similarly, the speaker recognition process can be grouped into two phases; enrollment and verification - the former develops the database while the latter matches the audio input to the database [156, 192]. The speaker recognition system also falls under two categories of text-independent and text-dependent [58].
The tabular summary of audio recognition categorization is given in Table 2.2.

Visual A camera serves as a sensor which captures the images that will be processed by the robot. The visual process consists of three modules of face detection and tracking, face recognition and facial expression recognition.

Detection and tracking Face detection is the process of locating faces in images. The system needs to know if a face is present in an image, together with its exact location in the image. The facial region is then extracted and passed to the recognition and analysis modules. The important requirements of a well designed face detection system are a high frame rate, a low false alarm rate, a wide range of working distances, and the ability to cope with different lighting conditions. In Lovotics application, AdaBoost-based face detector is used, which employs Haar-like classifiers, arranged in a cascade structure, with high accuracy and robustness against observations with low resolutions or varying illumination conditions [245]. The cascade classifiers can detect faces very rapidly by rejecting non-facial background regions in the early stages of the cascade. Besides detection, the system needs to track the moving human faces in real-time. A variety of tracking algorithms have been proposed, such as the Kalman

Table 2.2: Audio Recognition Methods

<table>
<tr><td rowspan="10">Audio Input</td><td rowspan="4">Voice Recognition</td><td rowspan="2">Dialogue based</td><td>Speech pattern recognition</td></tr>
<tr><td>Natural Language Processing (NLP)</td></tr>
<tr><td rowspan="2">Non-Dialogue based</td><td>Mel-Frequency Cepstral Coefficients (MFCC)</td></tr>
<tr><td>Basic parameters (pitch, loudness etc)</td></tr>
<tr><td rowspan="6">Speaker Recognition</td><td rowspan="2">Methodology based</td><td>(1:1) matching - verification</td></tr>
<tr><td>(1:N) matching - verification</td></tr>
<tr><td rowspan="2">Phase based</td><td>Enrollment (Developing database)</td></tr>
<tr><td>Verification (verifying identity)</td></tr>
<tr><td rowspan="2">Dependency based</td><td>Text-dependent (textual database)</td></tr>
<tr><td>Text-independent (speech recognition)</td></tr>
</table>

filter [236], conditional density propagation [120], and the Particle Filtering algorithm (also known as Sequential Monte Carlo method (SMC) [73]. The proposed tracking process is based on the Camshift object tracker [32], which uses color histogram [27] and a deterministic algorithm.

Recognition Face recognition refers to a capability to identify the facial images seen by a camera system. A robust face recognition algorithm requires it to operate reliably under varying conditions of illumination and background, and especially the orientation of the subjects' faces. Popular approaches to the problem field include algorithms such as the Eigenface [238] and the Fisherface method [23]. However, a common problem with these approaches is that the recognition rate becomes very unreliable as the subjects' orientation and position changes. The algorithms' accuracy also becomes very questionable under different background and illumination conditions. Numerous pre-processing steps will thus have to be carried out before the face recognition kicks in, such as illumination normalization and scaling. The use of a moving camera may overcome some of these problems by zooming in to the face of interest before recognizing the face. A more robust approach to face recognition is the Hidden Markov Model method [173] and a variant of that is the Embedded Hidden

Markov Model (EHMM) [174] which has used in Lovotics vision system.

Facial expression recognition Facial expressions can be defined as the change in the relative positions of various facial features due to different emotions felt by the person. There are six basic emotions: happiness, sadness, fear, disgust, surprise, and anger [66]. Each of them is associated with one unique facial expression. Facial expression recognition approaches can be divided into two main categories: a target-oriented approach, to infer the facial expression from still facial images and a gesture-oriented approach, to utilize temporal information from a sequence of facial expression motion images.
Proper utilization of dynamic facial motion information can prove invaluable and critical to the process of emotion recognition and interpretation [2]. The temporal patterns of different expressions are used in extracting the feature vectors from the sequence of images [149]. In the system using a 3D face mesh, the position of attachment of the facial muscles and the elastic properties of the skin are estimated in model-based facial image coding which achieved a recognition rate as high as 98% [147]. Independent component analysis methods have also been used to achieve a 95.5% average recognition rate [61]. Another approach involves using multi sensor information fusion technique with Dynamic Bayesian Networks (DBNs) [266]. Another method is to average facial velocity information over identified regions of the face and cancel out rigid head motions to develop a real-time recognition system for facial expressions [5]. Series of experiments can be used to compare methods. For example a systematic comparison of machine learning methods like AdaBoost, support vector machines, and linear discriminant analysis applied to the problem of fully automatic recognition of facial expressions was performed [152].

Touch Touch is the first of our senses to develop, and it provides us with our most fundamental means of contact with the external world. The skin, and the receptors therein, constitute both the oldest and the largest of our sense organs. We use touch to share our feelings with others, and to enhance the meaning of other forms of verbal and non-verbal communication [20, 60]. For example, our eye contact with other people means very different things depending on whether or not we also touch them at the same time. As Field [74] points out `Touch is ten times stronger than verbal or emotional contact, and it affects damned near everything we do. No other sense can arouse you like touch. We forget that touch is not only basic to our species, but the key to it.´The sense of touch provides a very powerful means of eliciting and modulating human emotion.
As researched by Gallace [88], there are various disciplines relevant to interper-

sonal touch research including cultural anthropology, cognitive sciences, neuroscience and social psychology. There are many areas like art and design, virtual reality, long distance communication, marketing, ergonomics and engineering and robotics, which are benefited by these studies.
The effect of touch and its study for human-robot interaction involves the usage of touch as input. It is considered to be a strong input sensor for detecting the proximity of a person. Touch also denotes the closest possible position of one person with respect to another person or robot. Thus, it plays a key role in studying the intimacy developed in interpersonal relationships or the extent of love developed in human-robot interaction.
Unlike humans, robots can not experience the sensations developed with different types of touch. Hence, the factors like place of touch and pressure applied are used for differentiating different types of touch input and the corresponding behavior of the robot is decided. The research done by Micire [164] provides a new way of interacting with robots, through multi-touch. The user evaluation showed that multi-touch interface is preferred and yields in superior performance. Another notable work by Kato [135] showed the use of multi-touch as input for controlling multiple mobile robots. From all these studies, it is evident that touch provides a strong interface for interacting with robots and hence evaluating the compatibility or love developed during the interaction.

2.2.1.2 Artificial intelligence

In human beings, emotions are not computed by a centralized neural system and operate at many time scales and at many behavioral levels [7]. Human Love and social bonding employ a push-pull mechanism that activates reward and motivation pathways [71]. This mechanism overcomes social distance by deactivating networks used for critical social assessment and negative emotions, while it bonds individuals through the involvement of the reward circuitry, explaining the power of love to motivate and exhilarate [264]. Human empathy probably reflects admixtures of more primitive affective resonance or contagion mechanisms, melded with developmentally later-arriving emotion identification, and theory of mind/perspective taking [251].
Inspiring from human affection functionality, a multi-modal AI system is proposed for Lovotics which considers both short and long term effective parameters of affection.

Probabilistic Love Assembly Through many years of investigating human love, researchers have discovered several factors resulting in human love. Among them, factors such as propinquity, proximity, repeated exposure, similarity, desirability, attachment, reciprocal liking, satisfaction, privacy, chronemics, attraction, form and mirroring have been noted as some of the main reasons for love [10, 235, 145, 104, 248, 101, 78, 39, 42]. These effective factors could be taken into account in the robot to develop a systematic method for appraising level of love between a robot and a human. Further research on human's non-verbal behaviors was performed to investigate role of above parameters. That is presented later in this Chapter.

Artificial Endocrine System The natural endocrine system is a network of glands which works closely with the nervous system to secret hormones in the blood which affect the target cells to regulate the homeostasis, metabolism and reproduction [116]. Hormones are chemical messengers that play a key role in the endocrine system to maintain homeostasis.
Different approaches to implement the artificial endocrine system for robotics have been proposed. Adaptive neuro-endocrine system for robotic Systems [232] presented an adaptive artificial neural-endocrine system that is capable of learning online and exploits environmental data to allow adaptive behavior. Artificial homeostatic system [165] presents an artificial homeostatic system devoted to the autonomous navigation of mobile robots, with emphasis on neuro-endocrine interactions. Artificial neuro-endocrine kinematics model for legged robot obstacle negotiation [115] provides insight into the possibilities afforded by a novel artificial neuro-kinematics network, constructed to primarily aid obstacle negotiation for a hexapod robot, MAX II. Challenge of designing nervous and endocrine systems in robots [49] is discussed in conceptual terms for the feasibility of designing a nervous system and an endocrine system in a robot and to reflect upon the bionic issues associated with such highly complex automatons.

Affective State Transition Different methodologies have been used for dealing with the internal state of the robot. State machine [217] and fuzzy state machine [179] are simple proposed methods for that purpose. A multi-objective evolutionary generation process for artificial creatures specific personalities was proposed, where the dimension of the personality model is defined as that of optimization objectives [139]. In that approach an artificial creature has its own genome in which each chromosome consists of many genes that contribute to defining its personality. As a biological approach, the finger blood pulse fluctuations is used for developing the online system to estimate a driver's internal state [108].
A large number of studies employed the OCC model [183] as the fundamental model of emotion. For example, it has been integrated for modeling the emotions in the embodied character [21] or to develop a distributed and computational model which offers an alternative approach to model the dynamic nature of

different affective phenomena, such as emotions, moods and temperaments, to provide a flexible way of modeling their influence on the behavior of synthetic autonomous agents [241].
TAME is framework for affective robotic behavior that deals with an exploratory experimental study to identify relevant affective phenomena to include into the framework in order to increase ease and pleasantness of human-robot interaction. TAME stands for Traits, Attitudes, Moods and Emotions, the four components of the Personality and Affect module that is responsible for producing affective behavior [168, 167].
Machine intelligence needs to include emotional intelligence and demonstrates results toward the goal: developing a machine's ability to recognize the human affective state given four physiological signals and compares multiple algorithms for feature-based recognition of emotional state from this data [187].
Affective state transition can be designed as an emotional model. Energy and tension are known to be the two principle parameters for representing the emotions of a human being [198, 229]. Based on this fact emotional categories can be mapped to arousal, valence, and stance dimensions in a robot [34].

2.2.1.3 Output

In order to design and develop appropriate behaviors for the robot an extensive research on nonverbal behaviors was performed.

Nonverbal behaviors Nonverbal behaviors can be defined as human actions and reactions without using words that can be used during the communication and often done subconsciously. Facial expressions, hand gestures, body posture and nonverbal sounds are the most common types of this form of behaviors. A significant amount of our daily day to day communication occurs in the domain of nonverbal aspects [163].
As such, the role of nonverbal behavior in human interactive emotional expression is investigated in order to imitate that in the context of human-robot interaction and its implication for the progress of Lovotics.
In order to pave the way for Lovotics research, several nonverbal behaviors of the human being are investigated through psychological studies and categorized into 8 main groups according to form, cause and functionality of them. These categories are listed in Table 2.3 and pertinent nonverbal behaviors are described.

Paralanguage Paralanguage is the study of the nonverbal elements contained within speech that can convey meaning and emotion. Paralanguage may be expressed consciously or unconsciously and includes elements such as pitch and volume of sound. Paralanguage parameters plays a large role in how we

Table 2.3: Nonverbal Behaviors Categories

Category	Description
Paralanguage	Nonverbal vocal features that accompany speech in order to communicate specific meanings
Gesture	Non-vocal bodily movement intended to express meaning
Posture	Human body position and configuration
Haptics	Touch oriented
Proxemics	Use and perceive the physical space
Chronemics	Use of time in nonverbal communication
Facial Expressions	All behaviors related to the face
Synchrony	Behavior mimicry/cooperation between interactants

perceive our social environment and have been found to have certain universal similarity, regardless of culture and race [18, 215].
It has been found that there are a number of paralanguage parameters that can categorize emotional states effectively [45, 211].
Below are five paralanguage parameters that are known to have an effect on human behavior and how they convey emotions according to audio researchers [212, 214]:

- I. *Number of harmonics*: In sound and audio, harmonics refer to the different normal modes in oscillating systems. By increasing the filter cutoff level from a technical perspective, which is through conserving higher number of harmonics from a natural perspective, one is more prone to the feelings of potency, anger, disgust, and surprise, while if the filter cutoff level is low, meaning a lower number of harmonics, an individual would then experience feelings associated with pleasantness, happiness, sadness and boredom .

- II. *Amplitude variation*: Amplitude variation refers to the degree of change of magnitude experienced within an oscillating system. Thus a system with large amplitude variation is one that fluctuates between loud sounds and soft sounds. As such, research has shown that smaller variations in amplitude can convey feelings of happiness and pleasantness, while larger variation are mainly associated with the feeling of fear.

- III. *Pitch*: Pitch is the perceived fundamental frequency of a sound. It is known that pitch contains certain parameters, which, after manipulation allows us to control and generate affective states that would result in different perceived emotions.

  - *a. Pitch Variation*: By applying smaller pitch variation, the emotional states corresponding to feelings of disgust, anger and fear can be generated, while larger pitch variations corresponds to feelings of happiness, surprise and pleasantness.
  - *c. Pitch level*: The contours of the pitch also play a role in manipulating affective states of emotions. Pitch levels refer to how sharp or low a perceived sound is. A sound that is of a high pitch level would sound shrill and piercing to the ear, while a low level pitch would be deep and low sounding. Higher levels of pitch have been known to correspond to feelings of surprise, anger and fear, while lower pitch levels generally signifies boredom, pleasantness, and sadness.

- IV. *Tempo*: In audio, tempo refers to the speed or pace at which sound is generated or played. Thus, a slow tempo, or a slower pace is often associated to feelings of sadness, boredom and disgust, while a faster tempo corresponds to feelings of surprise, happiness, fear and anger. Tempo is one of the main paralanguage parameters that has a very obvious impact on the human emotional states.

- V. *Envelope*: A sound envelope is a method used to control the parameters of a sound, such as amplitude and frequency by means of a digital filter. A sharper envelope conveys feelings of surprise, happiness, pleasantness, and activity while a more rounded envelope would generate audio that invokes the feelings of disgust, sadness, fear, and boredom.

Gesture Gestures are defined as a series of non-verbal bodily movement that is expressive of thought or feeling. Gestures can be used in place of verbal speech, or can be used in coordination with verbal speech to reinforce the message. A main feature of gesture is that it should be done with a certain degree of voluntarism. Therefore, subconscious or reflexive actions such as tears welling up or jumping up when frightened are therefore not considered to be gestures. However, it should be noted that it has been shown that not all gestures are universal, and often gestures differ according to culture and language [137].

- I. *Head gestures*: Examples of head gestures are such as shaking one's head when one does not agree or to convey the meaning of denial [1]. Conversely, the gesture of nodding one's head carries the meaning of approval and affirmation. Such acts of nodding or shaking one's head is common practice among the different cultures in the world, although the meaning it carries would differ from place to place. At times a speaker may utter a word/sentence that he/she rejects as inappropriate. At such instances lateral tremors of the head are observed as a gesture. Movement of the head may also depict uncertainty in the mind of the interactant. Statements

like `I guess´, `I think´, `whatever´, `whoever´, and similar expressions are generally associated with lateral shakes of the head. The trajectories of these movements may be quite contained. In such cases, the subject is not negating the statement but rather acknowledging another possibility or missing piece of information [160].
Head shakes also convey intensification. Lateral movements of the head often co-occur with lexical choices such as `very´, `a lot´, `great´, `really´, `exactly´, and the like [98, 97].

- II. *Adapters (hand gestures)*: These refer to movements of the hand that entail manipulation of an individuals body part (such as scratching) or object such as clothing, spectacles via fidgeting movements. Adapters are not considered relevant to accompanied speech and nor are they meant to convey any message [258]. They are thought to refer to unconscious feelings or thoughts , or thoughts and feelings that the individual is not necessarily trying to communicate [105, 65].
Scratching motions in different areas may refer to different forms of emotion. For example scratching the head can refer to an action when the individual is attempting to recall something [1, 64, 68]. Nose scratching may refer to when an individual is feeling particularly good whereas ear scratching may take place when the individual is trying to concentrate [1, 67]. These similar motions albeit in different areas can refer to different feelings.

- III. *Symbolic gestures (hand gestures)*: Symbolic gestures refer to hand movements and configurations that have conventional meanings. Familiar symbolic gestures include the `raised fist´, `bye-bye´, `thumbs-up´. Unlike adapters, symbolic gestures are used intentionally and depict a clear communicative function. Every culture has a set of symbolic gestures familiar to most of its adult members, and very similar gestures may have different meanings in different cultures [258]. Although symbolic gestures often are used in the absence of speech, they occasionally accompany speech, either echoing a spoken word or phrase or substituting for something that was not said [258]. For example, motions involving movement of hands or head in shaking or other motions may refer to an extreme emotion of surprise and fear [1, 63].

- IV. *Conversational gestures (hand gestures)*: Conversational gestures are hand movements that accompany speech, and seem related to the speech they accompany. These gestures are not made in the absence of speech and appear coordinated with the speech itself. Unlike adapters, at least some conversational gestures seem related in form to the semantic content of the speech they accompany [258].

Posture Posture refers to the intentionally or habitually assumed position that a human uses in everyday life. It also can reflect a person's emotional state as well as subconscious reaction to the environment. Thus, posture is considered as one type of nonverbal behavior that conveys emotional and behaviorial information regarding an individual [101].

- I. *Posture mirroring*: Posture Mirroring is a form of posture synchronization that happens when an individual assumes certain posture, and his/ her partner assumes a similar or identical posture within a critical time spam. As in the case of movement echoing, synchronization level for posture mirroring is also proportional to the perceived interest level between the two interactants [101]. Thus, two individuals that are interested in each other would display higher levels of posture mirroring, and the converse is also true.

- II. *Sociopetal - sociofugal*: As a more specific example, this behavior denotes the relationship between the positions of one person's shoulders and another's shoulders. Primary orientations are defined as face-to-face, 45°, 90°, 135°, and back-to-back. The effects of the several orientations are to either encourage or discourage communication . For example, face to face postures encourage communication whereas postures at obtuse angles may signal avoidance [151, 40].

- III. *Leaning Head on palms*: An action that involves bending or leaning head on a surface or palms signifies a stressed or depressed emotion [1, 63].

Haptics Haptic communication is the means by which people and other animals communicate via touching. Touch is an extremely important sense for humans; as well as providing information about surfaces and textures it is a component of nonverbal communication in interpersonal relationships, and vital in conveying physical intimacy. It can be both sexual and platonic via actions such as kissing, hugging or tickling.
Haptic communication is very instrumental in communication emotions. Studies have shown that small variances in haptic behavior such as handshaking can communicate emotions effectively. The recognition of emotions via haptic behavior was found to twice as accurate as what would be expected by chance [32,33]. When an emotion was misidentified, it was usually mislabeled as the emotion with the same arousal or valence [223]. Overall the perceived emotion had the same arousal and/or valence in 90% of the trials (chance=75%) [223]. For example, sadness was expressed in slow, steady, and short movements, whereas joy was expressed in long, jerky, and fast movements [15].

- I. *Non Reciprocal Touch* : Subject sex and origin of touch (self vs. partner) had minor effects on attributed meanings. Subjects most often perceived these touches such as stroking, rubbing, tickling as expressing warmth/love, and rarely as expressing dominance/control. In addition, actions such as rubbing someone's back and touching one's arm were found to be exhibiting feelings of warmth/love whereas actions like tickling were perceived as being playful [188].

- II. *Interpersonal Touch* : Interpersonal tactile stimulation provides an effective means of influencing people's social behaviors (such as modulating their tendency to comply with requests, in affecting people's attitudes toward specific services, in creating bonds between couples or groups, and in strengthening romantic relationships), regardless of whether or not the tactile contact itself can be remembered explicitly [77, 40].
- III. *Changing form of particular behavior* : Similar actions with slight alterations in style or extent can lead to different emotional interpretations. For example, three different forms of hugs: criss cross, neck/waist and engulfing have different influence on intimacy [78].

Proxemics Proxemics is the study of set measurable distances between people as they interact [104]. It deals with how closely the participants are to touching, from being completely outside of body-contact distance to being in physical contact, which parts of the body are in contact, and body part positioning. An intimate distance could refer to an emotion of love, warmth or attraction whereas a public distance between individuals may refer to no interest from either individual.

- I. *Proximity*: Social distance between people is reliably correlated with physical distance, as are intimate and personal distance, according to the following delineations [70, 105]:
  - a. *Intimate distance* refers to a distance less than 46 centimeter. Zone for individuals who are involved in an intimate relationship; they can touch, smell, feel body heat, talk in a whisper, but cannot see the other person very well.
  - b. *Personal Distance* refers to a distance between 46 centimeter and 122 centimeter. Zone for individuals who are at a distance at which discomfort could be felt if that space is penetrated by someone whom the individual is not familiar with; each person can be clearly seen, and they can touch each other by reaching.
  - c. *Interpersonal Distance* refers to a distance between 1.2 meter and 2.4 meter. This zone is used for formal business purposes such as sitting across a desk from one another; body movements are clearly visible, and speech needs to be louder.

– d. *Public Distance* refers to a distance of greater than 3.6 meter. This zone is a distance used for important public figures; facial expressions are difficult to see, louder voice is needed to communicate, and body movements need to be exaggerated to be visible.

Proximity plays an important role in nonverbal communication. Interactants can either be comfortable or uncomfortable with presence of other interactants in different zones [105]. The above ranges provide a general guideline. Slight variations that depend on the culture, social situation, gender, and individual preference can exist [106, 235].

Chronemics Chronemics is the study of the use of time in nonverbal communication. The perception of time and its consequences in reacting to the perception is an important communication process. Across cultures, time perception plays a large role in the nonverbal communication process. Time perceptions include punctuality, willingness to wait, and duration of interactions. The use of time can affect lifestyles, daily agendas, speed of speech, movements and how long people are willing to listen [41].

- I. *Chronemics in sound*: Variation in speed of speech can cause different perceptions of emotion. A slower more deliberated speech may refer to feelings of sadness, boredom, and disgust, while a quicker speech corresponds to feelings of surprise, happiness, fear, and anger [214].

- II. *Hierarchically Patterned Synchronization* : Significant results were found for a phenomenon described as hierarchically patterned synchronization. For example, if a female is interested in a male, the interactants display time - bound patterns of movement. The patterns are pair-specific and independent from behavioral content. This rhythmic structure of interactions associated with time may refer to different kind of emotional feelings and behaviors [101].

- III. *Duration of an embrace* : Studies show that one, three, and five seconds hugs have different intimacy effect [78]. The duration of a particular physical action like hugging or touching can have different meanings in terms of feeling. It has been determined that longer hugs correlate to higher intimacy [78].

Facial expressions Facial expressions are defined as all behaviors as a consequence of the motion of one or more of the human face muscles. Facial expressions are an important means of conveying social information among humans. It has long been regarded as an integral part of nonverbal behavior. However, although there have been evidence that stronger emotions share a universal similarity in facial expressions, facial expressions do differ according to language and culture, as is the case with many other nonverbal behavior [63].

- I. *Laughter*: Laughter can be considered both a facial expression, as well as a verbal behavior. Laughter is considered as the visual cue, which is also a common facial expression that is able to create an obvious and yet discreet and playful message of either aversion or excitement, according to the situation [100, 243]. If laughter does not succeed a joke or a humorous event, its function is more conversational. Depending on the preceding action/converstation, laughter can be used to express confirmation, doubt or interest. This scientifically explained by the variation if the fundamental frequency of the laugh as well as parameters such as duration.

- II. *Rapid eye blinking*: Rapid eye blinking would mean that a person is tired, and a blank or neutral expression normally indicates that a particular individual is lost and cannot understand whatever that is being conveyed [1].

- III. *Raising eyebrow*: Eyebrow movements play an important role in depicting emotion. Expression of each of the six emotions (happiness, sadness, anger, fear, disgust, and surprise) was seen to involve a distinct combination of movements in the three main facial components; and the upper component, notably the eyebrow, was found to play a key role in the expression of a number of emotions, including happiness, surprise, and anger. For example, in the expression of anger, the eyebrows are typically pulled downwards and inwards, perhaps in combination with squinting eyes and a tightly closed mouth [201]. In addition, raising one's brow can show that a person is indifferent to the situation that is occurring [1].

- IV. *Smile*: Smiles types include amused, polite, embarrassed, and pain smiles. It has been found [81] that smiles perceived as amused were more likely to have open mouth, have larger amplitude and more abrupt onset and offset. Smiles perceived as embarrassed/nervous were more likely to include downward head movement. Smiles perceived as polite were more likely to have closed mouth and smaller amplitude. In addition, polite smiles have been found to have shorted duration that other smile types . A long smile is generally associated with a person enjoying the atmosphere around him, while a closed eye smile is an expression of happiness [1]. Also, the onset and offset time of the smile has been found to be shorter for amused smiles than other types [81]. Smiles that have a more consistent duration and smoothness depict enjoyment [82]. Smiles can also be interpreted as a feeling of contentment or satisfaction.

- V. *Forehead Wrinkles*: A behavior such as wrinkles on the forehead may signify concentration or frustration [1, 63].

Synchrony Synchrony in the field of social interaction is defined as the characteristic behavior displayed by interactants that are generated via imitation or cooperation. Research shows that interactants develop liking to other interactants who tend to mimic their actions and behaviors [19]. These interactants display pro-social behavior to those that mimic their actions [240]. ``Put simply, behavioral mirroring facilitates social interaction˝[155].

- I. *Movement echo* :Movement echoing is a synchronization phenomenon which is exhibited when an individual perform a certain movement, and person B performs a similar or identical movement within a critical time span. It is found that the higher the interest between the interactants, the more synchronized both interactant's movements become [101, 155].

2.2.2 Love evaluation

To evaluate the efficiency of the system including hardware, software, and especially the developed artificial intelligence algorithms, an evaluation is required. The conventional method of evaluating a system consists of evaluation of modules separately whereas the adopted method of evaluation through user study of the entire system provides a general feedback about overall progress of the robot.
Prior to this, numerous researches were done to measure the extent of love and love style in human interpersonal relationships. The previous studies provide the information about how the love among two entities should be evaluated and how the extracted information can be used to find the developed love style. As no prior research has been done for measuring love in human - robot interaction, the studies on human interpersonal relationships were adapted with some transformation to make them suitable for human - robot interaction. The method of user study was adopted to measure love in human - robot interaction. In order to perform an effective evaluation, the psychology of love in human interpersonal relationships was studied and was carefully replicated for human - robot interaction and a set of relevant questions was formed. A questionnaire was designed to extract the information about the feelings and extent of love established in the interaction.
The obtained results of evaluation shows how various parameters influence the feeling of intimacy, hence providing an elementary guideline for developing new generation of Lovotics robot with higher degree of bi-directional love. The study also provides the information about the relevance and irrelevance of any robotic feature in the development of bi-directional love during interaction. The

adopted method opens a new research scope for enthusiasts of human - robot interaction. The gender based analysis of the results would help in studying the psychology of males and females towards robots, thus providing useful information about the features which make a robot ``attractive for males'' and ``attractive for females'' . Similarly, the features which make a robot ``attracted towards males'' and ``attracted towards females'' can also be found.

Love is considered to be a complex neurological phenomenon, relying on trust, belief, pleasure, and reward activities within the brain, which is, limbic processes [71]. In science, love appears to be a hypothetical and multi-dimensional construct with many interpretations and implications, and often involves the context in which it is defined. However, early phases of love, such as falling in love can be directly evaluated by studying the neurobiology and user experience [71, 264].

Functional Magnetic Resonance Imaging (fMRI), by studying the neural activity of brain, and user-study, by analyzing the love through a self-report questionnaire, are two general scientific methods of human love measurement.

The fMRI method uses the intrinsic magnetic properties of a substance to produce images of internal anatomical structures such as the brain. By taking a rapid series of functional images, it is possible to infer which regions of the brain are more active during certain tasks like interpersonal processes. Several recent cognitive neuroscience studies have examined the brain's involvement in interpersonal processes and development of love [264, 157, 103].

User study is a procedure of asking the user about their experience regarding any new technology, innovation or ideas they have put across. Surveys and structured interviews are two types of extensive research methods which are generally used for performing user studies. These methods have been used by many researchers to evaluate human love [159, 114, 113].

The evaluation of love through user study can be classified into various love-scales [159]. These love scales are used for determining different love aspects of a relationship.

The most commonly used love scales are Passionate Love Scale, Strenberg's Triangular Love Scale, Lasswell's Love Scale, and Love Attitude Scale (LAS). Passionate Love Scale analyzes the intensity of love as romantic love, infatuation, love sickness, or obsessive love [112, 111]. Sternberg's Triangular Love Scale is used for determining the intimacy, passion, and commitment factors of a relationship [226, 225]. Lasswell's Love Scale includes parameters including love, liking, storge, and agape [142].

The Love Attitude Scale (LAS) uses Lee's ``colors of love'' [144, 143] theory to determine the love style of a person. Many researchers, including Hendrick [114, 113] and Richardson [193] have used this method for analyzing and evaluating human love. This method has been widely researched; hence, it has been

Table 2.4: Love Measurement Methods

Evaluation Of Love		
Human-Human Love		Human-Robot Love
Functional MRI (fMRI)	User Study (self report)	User Study (self report)
Neural activity study	- Sternberg's Triangular Love Scale - Passionate Love Scale - Lasswell's Love Scale - Love Attitude Scale (LAS)	Lovotics Love Attitude Scale (LLAS)

adapted and transformed as **Lovotics Love Attitude Scale (LLAS)** for the evaluation of human - robot love. By using LAS, the love style of a person towards another person, often referred as ``colors of love´´ is identified. Similarly, by using LLAS, the love style of a person towards a robot can be identified. A summary of the love measurement methods is presented in Table 2.4.

The researches by Lee [144, 143] and Hendrick [114, 113] show how the six ``love styles´´ are used by people in their interpersonal relationship. These love styles are considered to be the models of how people love and are briefly explained as follows:

- **Eros** - Sentimental and intuitive physical attraction. It mostly refers to stereotype of romantic love and it s a sensual style of love. It can also refers to love at first sight. Erotic lovers choose their lovers by intuition or chemistry.
- **Ludus** - Enjoyment of the fun of playing. It is mostly about quantity than quality of relationship. Ludic lovers choose their partners by playing the field, and quickly recover from break ups.
- **Storge** - Affection that slowly develops from companionship. Storgic love develops gradually out of friendship, and the friendship can endure beyond the breakup of the relationship. Storgic lovers place much importance on commitment.
- **Pragma** - Finding desired attributes rationally. Pragmatic lovers think rationally and realistically about their expectations in a partner and want to find value in their partners.
- **Mania** - Volatile and obsessive need. Manic lovers often have low self-esteem, and place much importance on their relationship.
- **Agape** - Selfless altruistic and sacrificial devotion. Agapic lovers view their partners as blessings, and wish to take care of them.

Chapter 3

Method

3.1 Design

The main goal of Lovotics robot is to establish and reinforce the feeling of love between the human and the robot. Hence theories for human love can be employed and utilized to institute indispensable design aspects of the robot. Different love styles were considered for Lovotics and various design theories were applied to Lovotics design to generate love styles. In this way, design parameters for Lovotics could be found.
As discussed in 2.2.2, Eros, Ludus, Storge, Pragma, Mania, and Agape are known as love styles or colors of love. These six basic models of love are widely used in human love studies. These styles were also investigated during Lovotics research and it was attempted to apply the essence of each style in the robot design process.

Eros Aesthetic aspect of the design could emphasize this aspect of love.

Ludus Behaviors of robot play an important role in this aspect.

Storge Interaction through slow communication could gradually develop such mode.

Pragma Artificial intelligence of the robot could effect this aspect.

Mania The sense of ownership can satisfy the feeling of the need in the human being.

Agape Intuitive design considering nurture can lead to sense of care giving which would effect this style.

These styles were especially employed for evaluation of the developed robot in each series of development and improvement based on users feedback.

3.1.1 Robot design process

The Lovotics design process started with concept generation by investigating the concept of human love to define human - robot love. Afterwards for initial target finding, research analysis, and pre-evaluation survey were performed. Design theories and technics were applied to Lovotics design. Then design parameters were identified for the specific case of Lovotics robot. Several prototypes and alternative designs were developed and evaluation and refining process were applied to that before final system implementation and system integration. Specific design evaluation method was developed and the system was tested. Several aspects of the design improved gradually as evolution. Table 3.1 shows the overall design process of Lovotics robot.

Table 3.1: Lovotics Design Process

No.	Task	Description
1	Concept generation	Investigating human love to define human - robot love
2	Research analysis	Pre-evaluation survey for initial target finding
3	Applying design theories	Employing design theories and technics for Lovotics specific goal
4	Identifying design parameters	Investigating design parameters for love
5	Prototyping	Alternative design, evaluation, and refining
6	Implementation	System integration and development
7	Evaluation	Designing an evaluation method for System testing
8	Evolution	Improving several aspect of the design gradually

3.1.1.1 Concept generation

One of the primary requirements of the Lovotics research is to design a robot that loves and is loved by humans. Love is an abstract term. The first and most trying difficulty regarding this part of Lovotics research was to outline a definition for the every emotion which is required to be simulated. If these emotions could be recreated within a robot at its basic definition, then it was possible to design new definitions of the term which included robots in the picture. For this purpose the definition of Lovotics as presented in 1.1.3 is employed for design of a robot for Lovotics.

3.1.1.2 Research analysis

After establishing the general research concept of Lovotics, in order to realize design requirements multiple rounds of brainstorming, discussion, and refinement were carried out. Then a pre-evaluation survey has conducted to find the more clear imagination about the design.

Pre-evaluation survey Before making any attempt to design a robot which could accurately communicate the feeling of love, it was needed to get a better understanding of how people perceive love and objects. In order to do so questions were posed to instigate memories of love and being loved from a human-to-human context. Focusing on personal perspective, series of questions were designed that engaged the participant's previous experiences in order to prepare them for next set of questions.
In the second half of the survey, responses regarding whether or not people could get comfortable with the idea of loving robots were asked. These questions mostly dealt with whether they could imagine loving a robot, list some of their favorite objects, and what words they would use to define love with objects. These questions helped to define a behavioral model when designing the robot. Lastly, a more concrete understanding of the embodiment of physical qualities within an object when imagining a robot that could love and be loved was required. These questions helped to define a physical design for the robot, and also helped to define other modes of expression that the robot needed in order to engage with real humans.
The following are results from a survey completed by 70 participants of various age, race, occupation, and sex. The survey was conducted over the internet and participants were found through various social networking channels.
From pool of participants, less then half could not imagine loving a robot. A

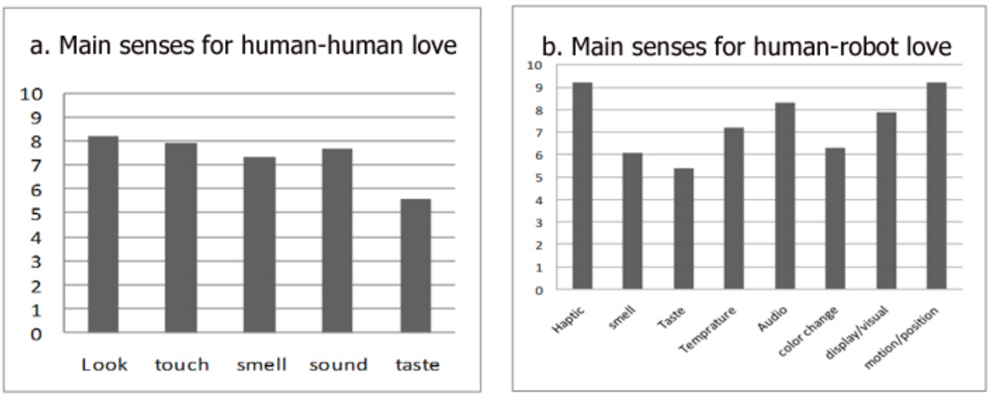

Figure 3.1: Questionnaire results for main sensory channels for Lovotics. a. Modalities for human-human love b. Modalities for human-robot love

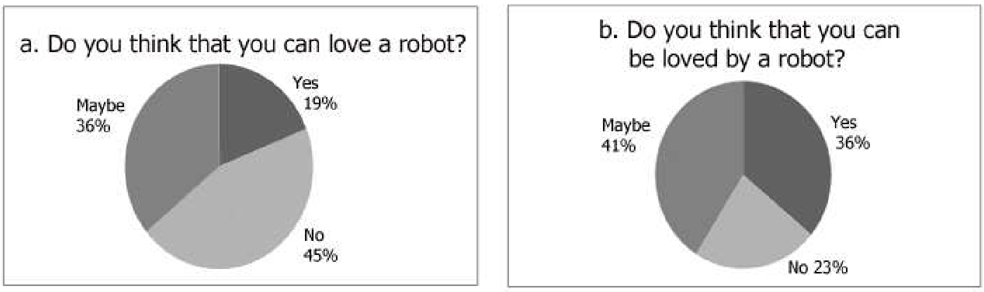

Figure 3.2: Questionnaire results for human-robot love acceptance. a. Accepting to love a robot b. Accepting to be loved by a robot

majority of the participants though were at least open to the idea, with 19% of participants actually believing that they could love a robot. These answers contrasted somewhat when the pool of participants were asked if they could in turn be loved by robots, with 77% open to being loved by robots. People are more willing to be loved and then to love, it seems.

Survey participants valued appearance above all sensations in regards to human-to-human love. Touch and sound came second in importance regarding human-to-human love, with smell a close third and taste being least important. Results from the survey discussing human-to-robot love pointed towards similar outcomes, where haptic, audio and motion played more important roles then smell, taste and color change.

The results of questionnaire show varied responses to how someone expresses or feels love. We have taken a multidisciplinary approach to understand the basic elements to love and recreated this in Lovotics robot. The senses tactile, audio, and visual were identified as the basic key senses used for expressing and feeling love.

3.1.1.3 Applying design theories

According to key design issues and questionnaire results, the function and form of the robot were designed.

Love in itself is intangible and very personal. If we consider the love, there is a sense of nurturing that is part of this relationship, and it is natural for us to be attached to someone or something that we nurture [239]. The aim was to evoke this nurturing capability in both humans and robots through Lovotics design and through this develop the sense of attachment that leads to love.

Several relevant design theories and technics were applied into the design of the robot.

Psychology of design Donald Norman introduced three levels of processing in design, namely visceral, behavioral and reflective [178]. These three levels of design are inter-related and the success of a product is usually determined by how good the design is at these three levels.

1. **Visceral design:** It is dominated by how products look, feel, and even sound. The underlying principles are usually hard-wired in, consistent across people and culture. For Lovotics, there is a need for it to encourage sociability with human being and thus its appearance is key as well as its tactile, audio, and visual input and output.

2. **Reflective design:** It is about what the product means to the user, the message it brings across, and its cultural impact. For Lovotics, the meaning will be to create a robot that loves the user and evoke feelings of love from him/her and the vision is to create a culture of love with robots, changing the human perception of robot beings without feeling.

3. **Behavior design:** It is about how the product performs. Good behavior design has four main components: function, understandability, usability, and physical feel. For Lovotics, its main aim is to infer sociability with humans through love with interactions that are comprehensible and intuitive.

Affective expressions Argyle, identified four affective expressions that can be displayed through body movement [8].

1. **Extreme inhibition:** Withdrawing or unnecessary movements.
2. **Depression:** Slow and hesitating, jerky movements.
3. **Elation:** Fast, expansive, and emphatic movements.
4. **Anxiety:** Fidgeting or hiding movements.

In the case of Lovotics, this concept was applied to the robot's behaviors to inculcate the perception of emotion.

Designing for pleasure Pleasure is a focus for many design situations that were once much more dominated by the more functional aspects of usability [24]. Lionel Target developed a framework for pleasure [231]. Patrick Jordan in the book `Designing pleasurable products´[128] employed such pleasure framework to apply four pleasure dimensions in design.

1. **Physio-pleasure:** It concerns body and the sense and arises from touching, handling or smell . For Lovotics a light weight robot with suitable texture is required for this dimensions. Also the robot should be responsive to human touches.

2. **Socio-pleasure:** It concerns facilitating social activities and arises from relationships with others. Relationship is a key issue in Lovotics and the robot should be capable of developing a social interaction with humans.

3. **Psycho-pleasure:** It concerns psychological pleasure and refers to cognitive or emotional aspects. Lovotics robot should satisfy the human emotionally during the interaction and generate positive feelings.

4. **Ideao-pleasure:** It concerns people's values and aspirations. In the case of Lovotics love is that critical value which needs to be considered carefully in design.

Designing sociable robot Cynthia Breazeal in the book `Designing sociable robots´[38] mentioned three issues for the robot's physical appearance which can be applied to Lovotics as well:

1. **Youthful and appealing:** Breazeal claims that it will be quite a while before we are able to build autonomous humanoids that rival the social competence of human adults and used infant-like appearance of a fanciful robotic creature of Kismet robot. Considering the gap to develop perfect humanoid robot, for Lovotics a simple and organic shape is designed instead of choosing the humanoid shape.

2. **Believable versus realistic:** A robot does not need to be realistic to be believable and humans are paretically sensitive in negative way to systems that try to imitate humans but inevitably fall short. These two point also support the idea to choose non-human shape for Lovotics robot and aim for a believable character.

3. **Audience perception:** Same as classical animations, a deep appreciation of audience perception of the robot is fundamental to form the interaction with the robot. Lovotics robot also needs to establish an appropriate set of expectations through design

Scenario Based Design Mary Beth Rosson proposed a scenario-based framework for human computer interaction [197]. The basic argument behind scenario-based methods is that descriptions of people using technology are essential in discussing and analyzing how the technology is (or could be) used to reshape

their activities. A secondary advantage is that scenario descriptions can be created before a system is built and its impacts felt.
Such approach was also employed in several stages of Lovotics design which instead of finishing the robot development and design evaluation through user studies, scenarios were employed to ask users opinion before experimenting real interaction with the real robot but with imagining the experience according to the scenario.

From software design to robot design Terry Winograd in the book `Bringing Design to Software ´[259] aims to improve the practice of software design, through thinking about design from a broader perspective, and exploring how lessons from all areas of design can be applied to software. He argues the role of artist in software design. For Lovotics design several designers were consulted with and been asked to design a robot with main functionality of love without considering technical possibilities. Software design is an older field compare to robot design and lessons can be learned from software for robot. As an example spiral model [29] as a software development process was applied to the design of the robot.

Spiral model The spiral model is a software development process combining elements of both design and prototyping-in-stages, in an effort to combine advantages of top-down and bottom-up concepts. This model was defined by Barry Boehm [29]. Also known as the spiral life cycle model (or spiral development), it is a system development method used in information technology. This model of development combines the features of the prototyping model and the waterfall model. The spiral model is intended for large, expensive, and complicated projects.
Such model was also applied in Lovotics design process where iterative and incremental development performed through deployment with the cyclic interactions between initial planning and end.

3.1.1.4 Design parameters

After deep understanding of the concept of love from one side and investigating various relevant design theories, these two issue were put together to identify Lovotics design parameters. Table 3.2 shows the main design parameters of Lovotics.

Form and function Communicating any sense of feeling let alone a synthetic expression of love is quite a challenge, to say the least. To feel and express emotions, a combination of signals engaging all the senses is important. Sound,

Table 3.2: Lovotics Design Parameters

Design parameter	Applied in Lovotics robot	Reason
Form	Organic semi-egg shape	Inculcating nurturing feeling
Sensors	Audio, vision, and touch	Based on initial survey
Color	white cover and RGB glimmering	Studies on Color
Size	small	Instigating sense of nurture and care giving
Weight	Light	To be able to held by humans
Affordance	Soft covering	Encouraging user to touch and conveying love
Familiarity	Left side of uncanny valley	Avoiding uncanny valley
Design complexity	Minimal design	To avoid complexity for the user to feel and understand
Anthropomorphism	Intuitive cute, organic and natural design	Attribution of love characteristics
Interaction	Slow communication	Developing long term love experience
Desirability	Innate superficial emotional connection	Desirability is the main design target compare to usability and usefulness

touch, and vision would all play a part in the success of intended solution. With such a monumental task set , all modalities were attempted to be addressed in order to create a framework for an expression of synthetic love. With the hopes to develop a new emotion where being human is not necessarily a requirement, the start point was with the idea that attraction would make its initial impact and developed a form that was pleasing not only to behold but to hold as well. There are some key points that were advised by interaction designers to be considered in designing the appearance of the robot. Firstly, the Lovotics robot should look timeless, representing no particular culture or generation. Children and adults should love and feel loved by it in equal measure. Secondly, there are differing tastes between genders. Males prefer objects with well defined straight lines or angles and in the case of love symbol, they prefer them to be less obvious or even better the lack of it. Females on the other hand can accept curvier, round and soft objects and obvious love cues being displayed [254, 261]. The appearance of the robot should be unisex using a simple and meaningful design. Males

should love it (probably) more for its novel technology and females should love it (probably) more for its display of affection.
Referring to the results of the initial survey, it was found that middle-aged people believed that between human-to-human interpersonal affection, looks (physical appearance) and touch (tactile feeling) were the most important, closely followed by sound. In contrast, haptic and motion/position feedback were the most important when discussing main sources for human-to-robot affection. The results of the questionnaire also showed that people preferred an organic shape to a geometric one for the robot. With these results taken into account, a form that was curvilinear and pleasing to the eye was developed. The suggested design of the robot was quite compact, almost infantile or pet-like in size and dimension to instigate a feeling of smallness, elegance, fragility, and vulnerability - something that one would like to nurture and take care of.

Size As it is supposed to fit in the hand, the size of the Lovotics robot should be small. Smaller things are likely perceived to be cute, less threatening and humans have the tendency to protect smaller things. Being small also allows the user to carry the robot with them. In addition to having small size, it should also be light in coherence with its size. A perception mismatch may be detrimental as all the positive feelings associated with being small may be diminished if the Lovotics robot is heavy. In addition, it is supposed to interact with the user at close proximity and it has to fit in the visual field of the user to capture his/her attention [221].

Color The choice of color can vary as different people like different colors. Pink or red could be a choice as they are representative of love [161, 126]. White or blue could be used as the primary color with some shades of other colors at some features. Blue is found to be the favorite color of many people and white is a color that induces trust [107]. In addition, the robot can be personalized by the user using accessories. By accessorizing the robot, the user can build up an ownership and develop more of a liking for the robot. This also allows the user to distinguish his/her robot from others. After some surveys, finally white color was decided as the color of the robot.

Affordance Affordance is a psychological terms that means giving a message from the object [177]. It defines the intuitiveness of the object and makes it easier to understand where the function of the product is. When the affordance of an object or environment corresponds with its intended function, the design will perform more efficiently and will be easier to use. Lovotics robots need to immediately give the message of love to the user of its function and purpose.

Uncanny Valley The uncanny valley [166] needs to be avoided and a more simplified representations of characters for the robot may be more acceptable to the human brain than explicitly realistic representations.

Interaction - reciprocation Love needs to be reciprocal to develop a relationship. The aim of Lovotics robot design was to generate the feeling of love and being loved during interaction to develop a bi-directional affection. Basically, no matter what the robot feels, it is important to expose the feeling of the love and that would be possible through behaviors and expressions.

Anthropomorphism Anthropomorphism is the attribution of human characteristics to animals or non-living things, phenomena, material states, and objects or abstract concepts [62]. Anthropomorphism should be considered in the design of the robot to generate natural feeling which will lead to love.

Slow communication The most accomplished individuals have usually acquired their distinctive level of skill over years or even decades [230]. Not only immediate interactive parameters are controlled by the robot but also robot needs to develop the affective connection with human in long term. The aim of Lovotics design was to generate long term interactive communication capability in addition to immediate reaction to develop a form of slow communication between the robot and humans.

Experience The robot requires to create a unique experience for human in long term. In Lovotics love is defined as a process which needs time. The aim of the design is to provide an unique experience for the user.

Minimal design Lovotics robot is designed based on the minimal design. Human society is not ready for complex Lovotics experience yet. Hence it was aimed to develop a simple but complete robot. The aim of the design was `A robot with simple hardware but sophisticated software´.

Usable, useful, and desirable Usable, useful, and desirable [206] are three closely linked terms but each implies a quite separate fact of design. Usable implies a strong and close connection between the functionality of the product and the abilities of the end user. Useful generally refers to the match between a system's functionality and the goals the user has in mind. Desirability is the fleeting idea associated with emotions [140]. Between these three issues, desirability is the main design parameter of Lovotics. The aim of the robot is not to perform any specific task or function but to develop strong emotional connection with the user.

3.1.1.5 Prototyping

During the design process of Lovotics robot, several prototypes in the form of sketch, animation, simulation, and models with different materials have been built. Lovotics robot is designed and developed through a series of prototyping, user studies, and surveys to achieve its final form and expressions. Some prototypes of the robot are presented in Figures 4.4 and 4.5. The 10 developed versions of Lovotics robot are presented in 4.2.1.

3.1.1.6 Implementation

Using concepts from the study of non-verbal behavior, emotions and love depicted via basic output channels as follows.
It has been shown that vocal patterns and tone can be used to express affective states [180]. In fact, in some situations such as content and context-free judgement cases, vocal cues have been as indicative of emotion as facial cues [210]. It has been found that there are a number of paralanguage parameters that can categorize emotional states effectively [45, 211]. Parameters such as pitch, tone, number of harmonics, and tempo can be used to decipher ones affective state.
The concepts of movement and posture are related to each other. It has been established that posture can indicate liking and interest and even level of comfort between individuals [8, 43, 72]. Actions such as leaning forward and closer proximity indicate attraction. Fast [72] describes that different postures are related to different emotional states. Hence by observing an individual's posture, his/her emotional state can be deciphered. Also, the recognition of emotions via haptic behavior was found to twice as accurate as what would be expected by chance [223, 15]. This strengthens a case to include a haptic input channel.
It has been seen from the study of human non-verbal behavior that movements, audio, and touch can be effective agents of exhibiting affective responses. These three methods are what the Lovotics robot uses to depict emotions. In addition, affective response from the robots behalf can also be generated using concepts of chronemics [212, 101] and synchronization [240] from the study of non-verbal behavior that are perceived via the haptic, visual, and audio input channels. Proximity [105] can be derived from audio and visual inputs and the reactions of the robot alter correspondingly.
For example, the robot may display greater affection in reaction to a longer touching action as was the case discussed in the varying effects due to the duration of an embrace. Also, if the robot is attached to a particular individual, it may tend to spend more time within the personal zone of the individual.
Research shows that body movements and posture reveal more about the actual affective state of an individual than facial expressions or even verbal communication [43, 72]. In fact it has been found that the affective state derived from posture and movement can be the true emotional state of the individual in spite

of contradiction with facial expressions [8, 43, 72].
From the study of human non-verbal behavior, it has been established that body movement and posture are more important than facial expressions, especially in the case of nonanthropomorphic robots. As such, in order to imitate body movements the robot was equipped with six basic behaviors:
1) Moving up and down to change height,
2) Rotation,
3) Navigation in two dimensional space,
4) Vibration,
5) Changing color,
6) Tilting.
Combination of these behaviors can be employed to express different emotions. These basic six behaviors are illustrated in Figure 3.3.
In addition to the appearance of the robot, the tactile, visual, and audio senses are key elements. These elements are expressed through the robot in the way it moves, changes shape, and produces sounds to express itself. It is a combination, sometimes subtle, of these elements that was understood by the humans as the robot expressing its love. Ten different versions of implemented robot are presented in Figure 4.5.

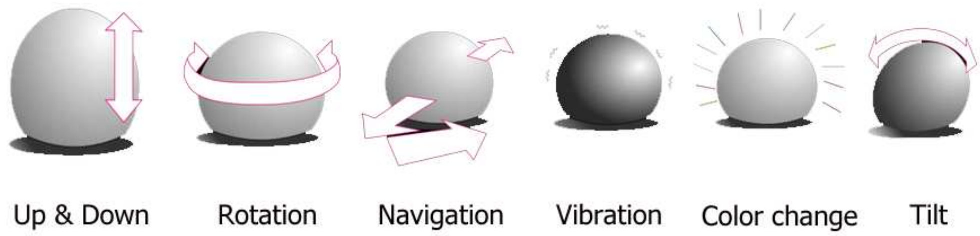

Figure 3.3: Basic behaviors of the Lovotics robot

3.1.1.7 Evaluation

The design of the robot is evaluated through user studies in order to receive feedback from users and improve the design. The novel proposed evaluation method of Lovoics is presented in 3.2.

3.1.1.8 Evolution

Several aspects of the Lovotics robot design were improved gradually after evaluations. Figure 3.4 presents an example of the improvement of the robot design after making several prototypes.

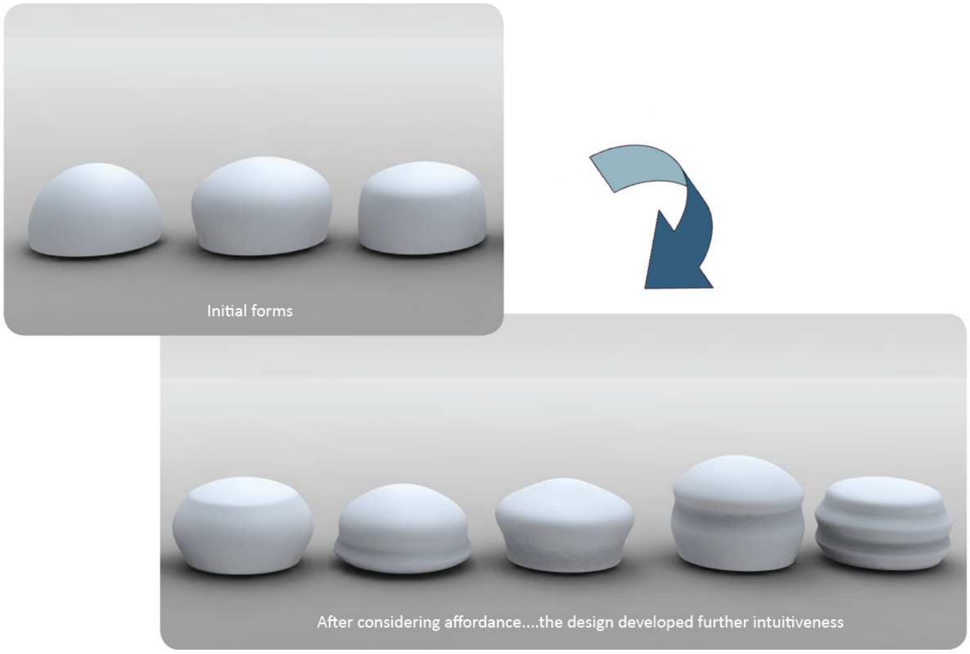

Figure 3.4: An example of evaluation in design of the Lovotics robot

3.1.2 Software system design

Modules of Lovotics software are presented in Figure 3.5.

3.1.2.1 Sensors

Audio system The Lovotics system utilizes audio channels as the main input parameter to induce the interaction process between human and robot. This is based on studies that audio plays an important role in communicating emotions and feelings between interactants [44]. Thus, both input and output audio are defined as as matrix *Aud* of five parameters, according to equation 3.1 which consists of tempo (*Tem*), pitch (*Pch*), number of harmonics (H_n), envelope (*En*), and amplitude (*Amp*). These variables are the main parameters that characterize emotional cues within a voice [45].

$$Aud = \begin{bmatrix} Amp & En & Tem & H_n & Pch \end{bmatrix} \tag{3.1}$$

An external microphone is connected processing unit to capture the audio of the humans talking to the Lovotics robot. Then audio input is processed in the audio analyzer module in order to identify the audio parameters associated with the audio input.

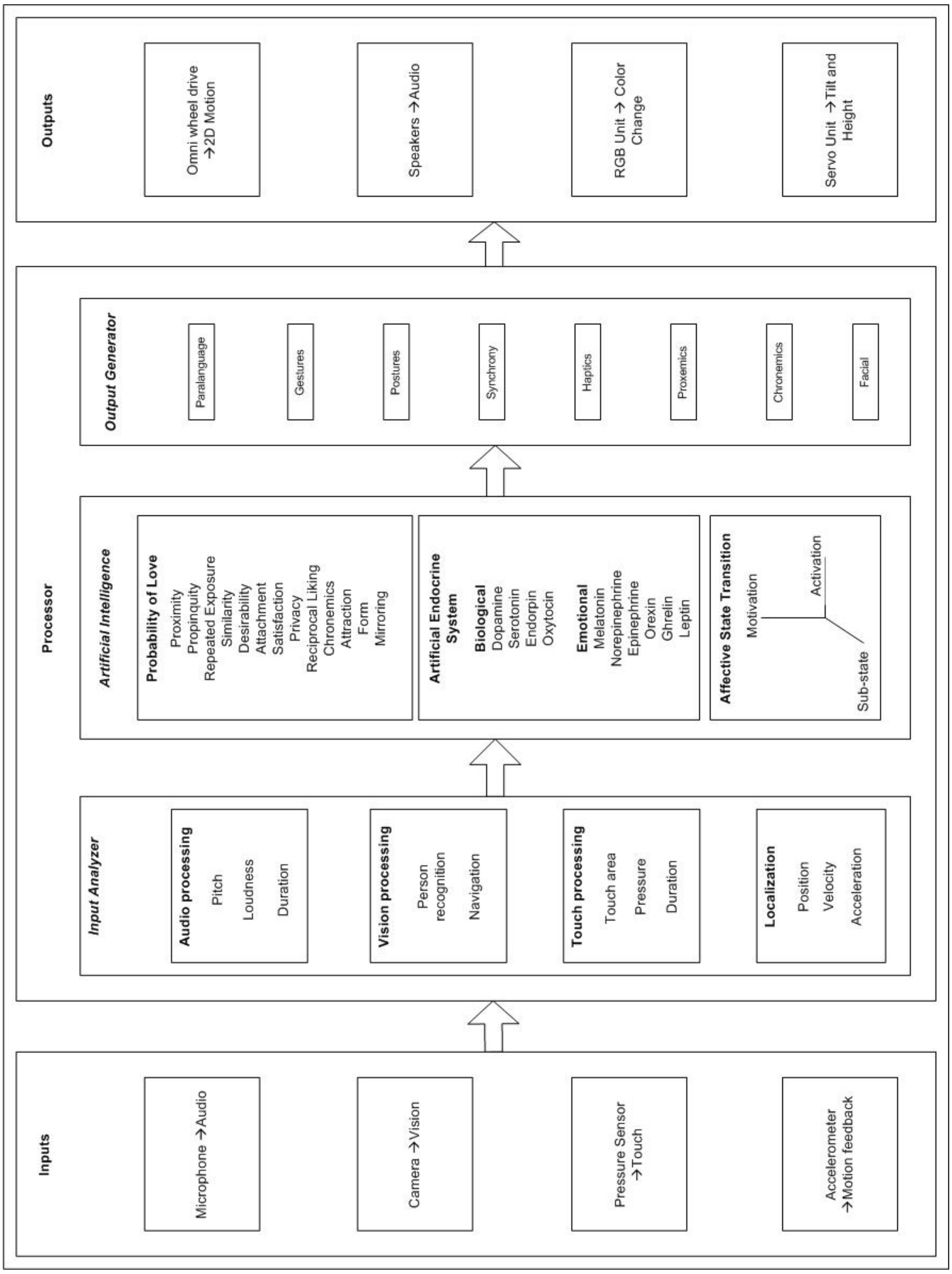

Figure 3.5: Different modules of Lovotics software.

Visual system Lovotics vision system uses Haar-cascade classifiers for face detection and a Camshift framework for face tracking. Face recognition is based on EHHM and expression recognition is based on nonlinear facial mass-spring model.

Face Detection and Tracking Module The Haar Cascade face detector detects the presence of the human face and subsequently, passes on the information of the detected face to serve as the input to the Camshift face tracking algorithm. The Camshift algorithm then tracks the latest location, size, and approximate rotated angle of the human face. The Haar cascade face detector provides reliable input information to the Camshift tracker to avoid tracking false faces. The Camshift tracker defines the region of interest in the image for the Haar cascade face detector to speed up the face detection phase. It also provides the ability to resume face detection when the Haar cascade classifier fails, in the event of extreme conditions like overly slanted faces, rapidly moving faces, etc. The detailed system description of the Haar Cascade Classifier and Camshift algorithms are explained below:

- **Haar-cascade classifier face detector**

  The prior step of face tracking is to determine the initial location of the face. The face detector is based on the Haar-like features [150], available in OpenCV [31]. A statistical model of the face, which is made up of a cascade of boosted classifiers is trained, using face and non-face example images of some small fixed size. Face detection is done using a small sliding window that scans the gray level image and each image patch is classified as either face or non-face. To deal with varying facial sizes the cascade is repeatedly scaled by scaling the coordinates of all rectangles of Haar-like features. Thousands of features are used as these shapes are applied at different positions in the small rectangular sub-image.
  A given feature's value is the weighted sum of pixels over the whole area added to the weighted sum over the dark regions of the Haar feature. A simple decision tree classifier, referred to as a weak classifier, processes the feature value. A complex classifier is iteratively built as a weighted sum of weak classifiers using an adaptive boosting procedure, the Adaboost [84]. The boosting algorithm for training a strong classifier is a weighted linear combination of $A1$ weak classifiers for given sample images of (a_i, b_i), where $b_i = 0, 1$ for negative and positive samples, respectively. The algorithm is as follows:

  - Initialize the weights $w_{1,i} = \frac{1}{2m}, \frac{1}{2l}$ for $b_i = 0, 1$ where m and l are the number of the negatives and positives respectively.

– For $z = 1, ..., A1$

1. Normalize the weights so that w_z is a probability distribution.

$$w_{z,i} \leftarrow \frac{w_{z,i}}{\sum_{j=1}^{n} w_{z,j}} \tag{3.2}$$

2. For each feature j, train a weak classifier ω_j

$$\omega_{j(a)} = \begin{cases} 1 & pr_j fe_{j(a)} < pr_j tr_j \\ 0 & \text{Otherwise} \end{cases} \tag{3.3}$$

A weak classifier $\omega_{j(a)}$ consists of a feature value $fr_{j(a)}$, a threshold value tr_j and a parity pr_j indicating the direction of the inequality sign,

3. The error is computed with respect to w_z:

$$\varepsilon_j = \sum_i w_i |\omega_{j(a_i)} - b_i| \tag{3.4}$$

4. Choose the classifier h_z with the smallest error ε_z.
5. By defining $up_z = \frac{\varepsilon_z}{1-\varepsilon_z}$, update the weights:

$$w_{z+1,i} = w_{z,i} up_t^{1-e_i} \tag{3.5}$$

where $e_i = 0$ if sample a_i is classified correctly and $e_i = 0$ otherwise.

– By defining $\tau_j = \log \frac{1}{up_z}$, the final strong classifier is:

$$\omega_{(a)} = \begin{cases} 1, & if \sum_{z=1}^{A1} \tau_z \omega_{z(a)} \geq \frac{1}{2} \sum_{z=1}^{A1} \tau_z \\ 0, & \text{Otherwise} \end{cases} \tag{3.6}$$

An intentional cascade is implemented in that way. It is a cascade of boosted classifiers with increasing complexity, the simplest classifiers come first and are intended to reject the majority of sub-windows before calling more complex classifiers.

- **Camshift (Continuously adaptive Meanshift)**

The Camshift is the Meanshift algorithm applied to video sequences using skin probability image (P_{skin}). A skin probability image is first generated based on the image pixels' location in the color histogram corresponding to the input region's color distribution. It then initializes a window with scale and location.
When a window is shifted more than a threshold, the following procedure is performed:

– Calculate mass center (mean) location of the portion of P_{skin} inside window :

$$\begin{cases} M_{00} = \sum_{x,y \epsilon W} P_{skin}(a,b) \\ M_{10} = \sum_{x,y \epsilon W} xP_{skin}(a,b) \\ M_{01} = \sum_{x,y \epsilon W} yP_{skin}(a,b) \end{cases} \tag{3.7}$$

$$x_c = \frac{M_{10}}{M_{00}}, y_c = \frac{M_{01}}{M_{00}} \tag{3.8}$$

– Center window at mean location (x_c, y_c)

The Meanshift applied on P_{skin} is a maxima search using a fixed size search window. The algorithm subsequently encapsulates the Meanshift in a loop for varying window size. At each iteration, Meanshift is applied with a given window size until convergence, then an ellipse is computed based on second order central moments, and the window size is updated from the resulting ellipse. The algorithm is as follows:

– Apply Meanshift on skin probability image P_{skin}, until convergence: store mean location (x_c, y_c) and M_{00}.

– Center W at (x_c, y_c) and increment its size by 10 pixels along both directions ±5 pixels along width and height to define a region of interest used to compute an ellipse based on inertia moments of skin probability image pixels inside the region of interest.

– Compute ellipse major and minor axis (with respective length l_1 and l_2) projections on horizontal and vertical direction to define next Meanshift window (with width of *wid* and height of *hei*):

$$wid = max(l_1 \cos\theta, l_2 \sin\theta)$$

$$hei = max(l_1 \sin\theta, l_2 \cos\theta) \tag{3.9}$$

– Magnify this rectangle by a 1.4 factor (approximately ± 20% along width and height) to define face search region in the next frame.

Face recognition The face recognition module is implemented by employment of the Embedded Hidden Markov Model (EHMM) algorithm.
Each state within the EHMM corresponds to a region on the input facial image. Observation vectors comprising of discrete cosine transform coefficients from each image regions are then extracted for analysis. The image region is segmented by passing a window of a predefined dimension over the image in a left to right, top to bottom fashion, each time ensuring a good degree of overlap of the window [205]. The discrete cosine transform maps the image data into the frequency domain. Coefficients over the lowest frequency region, where most of

the image signal energy is concentrated, are then used as the observation vectors for the EHMM.
The following parameters are defined for face recognition:

1. N_0, the total number of vertical super states present and $N_1^{(k)}$the total number of embedded states within the kth super state where $1 \leq k \leq N_0$.

2. $S_0 = \{S_{0,i}\}$, the set of super states present and $S_1^{(k)} = \{S_{1,i}^{(k)}\}$, the set of embedded states within the kth super state $1 \leq i \leq N_0$.

3. $A_0 = \{a_{0,ij}\}$, the transitional probabilities between super states, where $a_{0,ij}$ is the probability of transiting from super state i to super state j and $A_1^{(k)} = \{a_{1,mn}^{(k)}\}$, the transitional probability between the embedded states within the kth super state, where $\{a_{1,jk}^{(k)}\}$ is the probability of transiting from embedded state m to embedded state n within super state k.

4. $\Pi_0 = \{\pi_{0,i}\}$, the initial super state distribution probability, where $\{\pi_{0,i}\}$ represents the probability of the system being in super state i at $time = 0$ and $\Pi_1^k = \{\pi_{1,k}^k\}$, the initial embedded state distribution probability, where $\{\pi_{1,i}^k\}$ is the probability that the system begins from embedded state i of the kth super state at $time = 0$.

5. $B^{(k)} = b_i^k(O_{xy})$, the observation density function of embedded state i within the kth super state. O_{xy} refers to the observation vector at row x and column y. The observation vectors are characterized by a continuous Gaussian density function, with a finite number of mixtures. Following this

$$b_i^{(k)}(O_{t_0,t_1}) = \sum_{m=1}^{M} c_{im}^{(k)} N(O_{xy}, \mu_{im}^{(k)}, U_{im}^{(k)}) \tag{3.10}$$

where $c_{im}^{(k)}$ is the mixture coefficient of the mth mixture in state i in the kth super state. $N(O_{xy}, \mu_{im}^{(k)}, U_{im}^{(k)})$ represents a Gaussian model, where $\mu_{im}^{(k)}$ is the mean vector and $U_{im}^{(k)}$ is the covariance matrix. The kth super state can thus be described by the parameter set:

$$\Lambda^{(k)} = \{\Pi_1^{(k)}, A_1^{(k)}, B_1^{(k)}\} \tag{3.11}$$

The overall EHMM can be represented by λ with the following parameter set:

$$\lambda = \{N_0, \Pi_0, A_0, \Lambda\} \tag{3.12}$$

Training the EHMM:

A separate EHMM is made for each face by training, using a number of images of the same individual. The training process can be interpreted as an iterative attempt to adjust the model parameters $(\Pi_0, A_0, \Pi_1^{(k)}, A_1^{(k)}, B^{(k)})$ to fit the observed images as best as possible.

Recognition:

After training, recognition of an unknown face is once again carried out using a doubly embedded Viterbi algorithm [80]. For the given set of observation sequence from the input image, the probability of the maximum likelihood path based on each EHMM in the database is computed with the Viterbi algorithm. For each EHMM with parameters λ, and a given set of observation sequence denoted by O, $Argmax[P(O, Q|\lambda)]$ should be found, where Q represents the sequence of states which is attributed to observation sequence O. This is the probability of the most likely path (of states) which accounts for the input observation vectors. After the unknown face image is compared with all the trained EHMM in the database, the EHMM with the highest probability from the doubly-embedded Viterbi algorithm is selected to be the face's identity.

Facial expression recognition The facial surface deformation during an expression is triggered by the contraction of facial muscles. The muscle force is propagated through the skin layer and deforms the facial surface. The key points in analyzing the facial expressions are the attachment points of these facial muscles on the facial surface. The positions and velocities of these two key points are vectors and they vary with time during the facial expressive process. These data provide the information to analyze the dynamics of muscle contraction under the skin.
To represent the facial muscle construction, a model which involves nonlinear stress-strain relationship with variable elastic stiffness. As per the FACS model [66], 22 major facial muscles were used to generate the deformation map. These muscles are divided into seven groups based on their proximity and affected region [262].
As per the mass-spring model, the origin and insertion of the muscles are assumed to be connected by a spring. The origin of the muscle is the static point whereas the insertion is the driven point. To model the nonlinear behavior of the muscle as a spring, the mechanical soft-tissue model was used [267]. This model describes a nonlinear function that calculates the elastic stiffness and force for each functional muscle.
Suppose an arbitrary driven point x_i is connected to its corresponding fixed point x_j by a spring structure with rest length d_{ij}.

A function $K_{(x_i,x_j)}$ is defined as follows to modulate a constant elastic stiffness k_0:

$$K_{(x_i,x_j)} = [1 + (|\Delta x_{ij}| - d_{ij})^2]^{\alpha} k_0 \tag{3.13}$$

and the elastic force generated by an spring is

$$f_{(x_i,x_j)} = K_{(x_i,x_j)} \frac{|\Delta x_{ij}| - d_{ij}}{|\Delta x_{ij}|} \Delta x_{ij} \tag{3.14}$$

In equation (3.13), α is the non-linearity factor controlling the modulation.
The facial expression recognition system uses the deformation and motion parameters of facial features. The input to the system is a sequence of face images providing both spatial and temporal information, whereas the output is the classified facial expressions.
The facial image acquired by the camera is processed by the segmentation algorithm. This algorithm extracts various facial features such as position and shape of the eyebrows, eyes, nose and mouth. Then the algorithm also labels the Action Units (AU). These features are tracked in the video sequence to get the temporal information of each point.
For classification of facial expressions, an adaptive technique was used which is based on artificial neural networks, known as multi-layer perceptrons (MLPs). This technique is able to construct arbitrary decision boundaries and thus makes the distinction between different expression classes. For this multilayer network, inputs are the different facial muscles and outputs are emotion classes. Based on that, a model was build as shown in Figure 3.6.

Primary, hidden, and output layers of MLP correspond to the sensory data, facial AU and the classification layers respectively. Association of the expressions were classified with facial AUs as shown in Table 3.3.

Table 3.3: Association of Facial Expressions to AUs

Facial Expression	Action Units
Happy	6, 12
Sad	1, 4, 7, 15, 17
Disgust	9, 10, 17, 25
Surprise	1, 2, 5, 27
Angry	4, 7, 9, 17, 23
Fear	1, 4, 5, 7, 20

The class variable in the classification layer takes six states, namely happiness, sadness, disgust, surprise, anger, and fear. There is a set of attribute variables which has the following elements based on each facial expression; HAP, ANG,

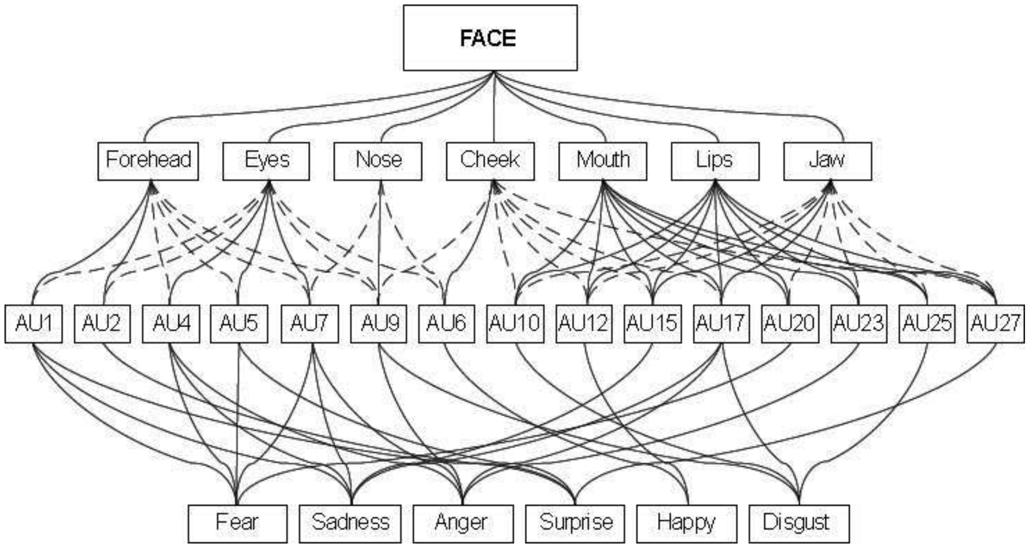

Figure 3.6: MLP model for classification of facial expressions. Face features, action units (AU), and facial expressions layers.

SAD, DIS, SUP, and FEA. The logistic activation function is used for each neuron as:

$$y_i = \frac{1}{1 + e^{(-v_j)}} \tag{3.15}$$

where v_j is the induced local field (weighted sum of all synaptic inputs plus the bias) of neuron j and y_j is the output of the neuron j. During recognition, the feature vectors derived from the feature generation procedure form a vector sequence.

$$\begin{aligned} F &= \{\vec{f}_{fr1}, \vec{f}_{fl1}, \vec{f}_{fr2}, \vec{f}_{fl2}, \vec{f}_{fr3}, \vec{f}_{fl3}, \vec{f}_{er}, \vec{f}_{el}, \vec{f}_{nr}, \vec{f}_{nl}, \\ &\quad \vec{f}_{cr1}, \vec{f}_{cl1}, \vec{f}_{cr2}, \vec{f}_{cl2}, \vec{f}_{mr1}, \vec{f}_{ml1}, \vec{f}_{mr2}, \vec{f}_{mr2}, \vec{f}_{jr}, \vec{f}_{jl}\} \end{aligned}$$

By considering k as:

$$k = HAP, SAD, ANG, SUR, DIS, FEA$$

The network produces six outputs $y_{out,k}$. The outputs are then normalized by a softmax function as follows:

$$z_k = \frac{e^{\tilde{y}_{out,k}}}{\sum_{r=1}^{6} e^{\tilde{y}_{out,k}}} \tag{3.16}$$

where $\widetilde{y}_{out,k} = \frac{y_{out,k}}{P(Cl_k)}$ represents the scaled outputs and $P(Cl_k)$ is the prior probability of class Cl_k. For MLPs, no output normalization is necessary because the outputs are always bounded between 0.0 and 1.0. Therefore, the scaled output was used for classification.

$$z_k = \frac{e^{y_{out,k}}}{\sum_{r=1}^{6} e^{y_{out,k}}} \tag{3.17}$$

For networks with mentioned six outputs, a typical class labeling rule is

$$E_k = argmax\{z_k\} \tag{3.18}$$

where E_k is the scaled output of the MLPs, $E_k \epsilon [0, 1]$ is a decision threshold. In this way, we obtain the final classification of facial expressions.

Touch system In the Lovotics system, touch input was taken through touch sensors mounted on the top of robot's skin. The area, location, and time period of touch are recorded in the database and corresponding behavior of the robot is reflected.
In the artificial intelligence module, this information is used in defining the proximity. The pressure applied while touching decides the closeness of user and modifies the behavior of the robot accordingly. As an example prolonged hard touch changes robot's state to happiness while frequent touches excite the robot.

3.1.2.2 Artificial intelligence

Probabilistic Love Assembly (PLA) PLA module is employed module to calculate probabilistic parameters of love between a human and the robot. This module employs audio and touch as channels of interaction between the robot and humans as illustrated in Figure 3.7. Visual channel of the robot is employed for detection, recognition, and expression analysis though.
Following definitions are used for the PLA module:

- Interactive zone of a robot is defined as an area in which a robot interacts with a human. It can be defined according to the physical properties of a robot e.g. size,
- Interaction happens when human locates inside interactive zone of a robot,
- Audio parameters include number of harmonics, amplitude, pitch, tempo, and envelope.

Also following notations are used:

- u is the interactive radius of the robot according to the interactive zone,
- C is the area of the environment,
- Ara_{rbt} is the area of the robot's surface,

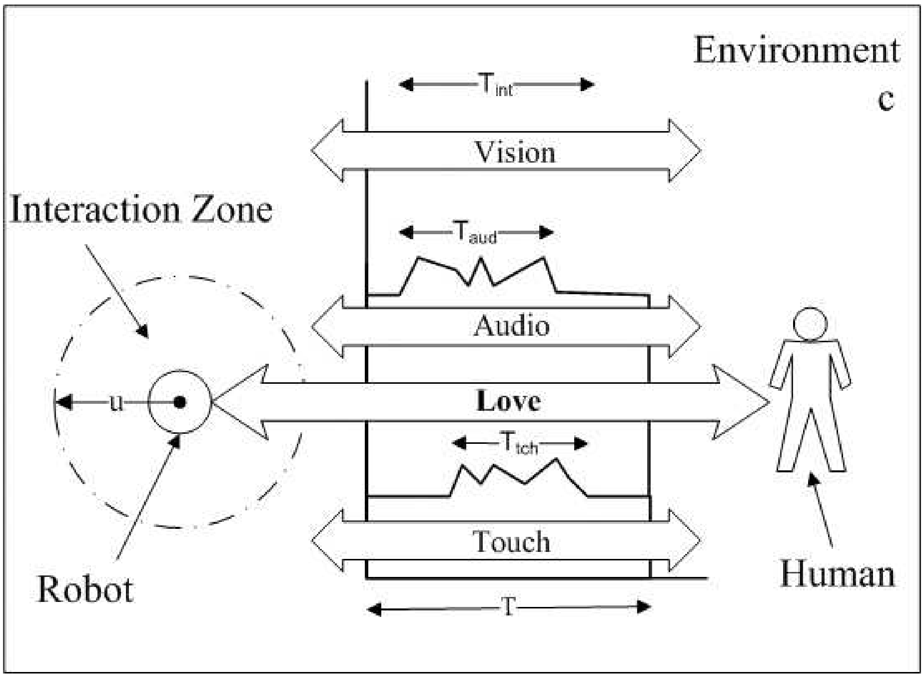

Figure 3.7: Schematic of the Probabilistic Love Assembly (PLA) module

- Ara_{tch} is the area of the robot's surface which is touched by the human,
- T is the time of considering the system for computation in the PLA module,
- T_{int} is the total time that robot and human are interacting either through audio or touch channels,
- T_{aud} is the total time of human-robot interaction via audio channel,
- T_{tch} is the total time of human-robot interaction via touch channel,
- T_{asy} is the total time that asynchronous similarity is visible in the human and robot audio parameters.

Based on psychological studies and the study of non-verbal behaviors, as presented in , probabilistic mathematical models for the 13 identified factors of love were formulated to provide an interpretation of the intimacy between humans and robots. Such mathematical models can be presented by a Bayesian network depicting the relationship between love and its causal factors.

1. **Proximity:** Physical distance between humans plays an important role in their feelings for each other [145, 104]. The effects of physical distance were mapped over into audio, with the aim of using audio proximity to emulate the effects of physical distance. A human is within the proximity of the

robot when the location of the human is inside the interactive zone of the robot. Hence the probability of proximity is chance of human to be located inside the interactive zone of the robot.

$$P(Prox) = \frac{\pi u^2}{C} \tag{3.19}$$

2. **Propinquity:** Propinquity represents the familiarity in terms of spending time with each other [10]. The robot and human spend time together if their distance is within the interactive zone and having interactions.

$$P(Prop) = \frac{T_{int}}{T} \tag{3.20}$$

3. **Repeated Exposure:** Repeated exposure to a particular individual can increase the familiarity and hence the feeling of liking for that individual [145]. A human and a robot have exposure when human moves from outside of the interactive zone of the robot to inside.

$$P(Expo) = P(Prox)(1 - P(Prox)) = \frac{\pi u^2}{C}(1 - \frac{\pi u^2}{C}) \tag{3.21}$$

4. **Similarity:** The degree of similarity between two people is directly related to the feeling of love [145, 10]. Similarity between a robot and a human can be calculated via comparing their audio parameters.

$$P(Siml) = 1 - \frac{|Audio_{Robot} - Audio_{Human}|}{Audio_{Range}} \tag{3.22}$$

The difference between human audio parameters ($Audio_{Human}$) and robot audio parameters ($Audio_{Robot}$) is found in Equation 3.22 and the probability of similarity within the audio range ($Audio_{Range}$) is cancellated.

5. **Desirability:** The desirable characteristics of the other can automatically release a strong attraction which can lead to the cases of love at first sight [145, 10]. In order to find the desirability of a person for the robot, audio input from the human can be compared to predefined desired audio parameters of the robot.

$$P(Desr) = 1 - \frac{|Audio_{Human} - Audio_{Desire}|}{Audio_{Range}} \tag{3.23}$$

By comparing the actual ($Audio_{Human}$) and desired ($Audio_{Desire}$) audio parameters of the human within the audio range probability of desirability could be calculated according to equation 3.23.

6. **Attachment:** Attachment represents the important emotional bonding between humans [235, 145, 39]. A human and robot are defined attached when the human stays within interactive zone of the robot for long time and human touches the robot. Hence, the overall probability of attachment depends on both interaction (int_{Aud}) and touch (int_{Tch}).

$$\begin{aligned} P(Atch) &= P(int_{tch} \cap int_{aud}) = P(int_{tch})P(int_{tch}|int_{Aud}) \\ &= \frac{T_{tch}}{T}\frac{T_{int}}{T} \end{aligned} \tag{3.24}$$

In the same manner, other probabilities can be calculated accordingly.

7. **Reciprocal liking:** Being liked by an other will increase the positive feelings to that other which will influence the feeling of love [145, 10]. Since it is not possible for the robot to directly understand the love feeling of the human, the probability of reciprocal liking can be estimated indirectly via observing human behaviors. We assume that human would touch the robot more if he/she likes the robot.

$$P(Recp) = \frac{T_{tch}}{T}\frac{Ara_{tch}}{Ara_{rbt}} \tag{3.25}$$

8. **Satisfaction:** Filling the needs of the other will increase the satisfaction of him/her and hence lead to a positive feeling of love [145, 10]. The robot needs to be close to the human being and to be touched by the human, so effective parameters of proximity, repeated exposure, and touch could effect the satisfaction of the robot.

$$\begin{aligned} P(Stfc) &= \frac{\pi u^2}{C}\frac{\pi u^2}{C}(1-\frac{\pi u^2}{C})\frac{T_{tch}}{T}\frac{Ara_{tch}}{Ara_{rbt}} \\ &= \frac{\pi^2 u^4}{C^2}\frac{T_{tch}}{T}\frac{Ara_{tch}}{Ara_{rbt}}(1-\frac{\pi u^2}{C}) \end{aligned} \tag{3.26}$$

9. **Privacy:** Spending time together and have a close interaction with each other can also improve the love feelings [145]. The robot and human have private time together if their distance is within the interactive zone and having interactions.

$$P(Prvc) = \frac{\pi u^2}{C}\frac{T_{int}}{T} \tag{3.27}$$

10. **Chronemics:** Chronemics is the study of the use of time in nonverbal communication [42, 248, 78]. It can be modeled as a function of asynchronous similarity time, touch interaction time, and audio interaction time.

$$P(Chrn) = \frac{T_{asy}}{T}\frac{t_{tch}}{T}\frac{T_{aud}}{T} \tag{3.28}$$

11. **Attraction:** Interpersonal attraction acts like a force drawing people together and influence the feeling of love [145]. Attraction between a human and a robot can be modeled as a function of time, force and area of touch:

$$P(Atrc) = \frac{t_{tch}}{T}\frac{f}{F}\frac{Ara_{tch}}{Ara_{rbt}} \tag{3.29}$$

12. **Form:** The form of interaction is also important in formulating love states [78]. Force and area of touch generate the form of interaction between the human and the robot.

$$P(Form) = \frac{f}{F}\frac{Ara_{tch}}{Ara_{rbt}} \tag{3.30}$$

13. **Mirroring:** Mirroring refers to matching the audio parameters of our robot with that of the person. It has been shown that higher degree of synchronization between interactants are reflective of higher levels of interest between them [101]. Asynchronous audio variables of the robot and human could be compared to find similar properties in different time.

$$P(Mirr) = \frac{T_{asy}}{T} \tag{3.31}$$

According to the presented probabilistic nature of the above 13 parameters, a Bayesian network is employed to link audio, touch, and location to these effective parameters in order to estimate the long-term probability of love. Proposed Bayesian Network is presented in Figure 3.8. This Bayesian network analyzes various causal parameters of love between the robot and the human that can be categorized in three groups:

- Human and robot distance and their interaction,

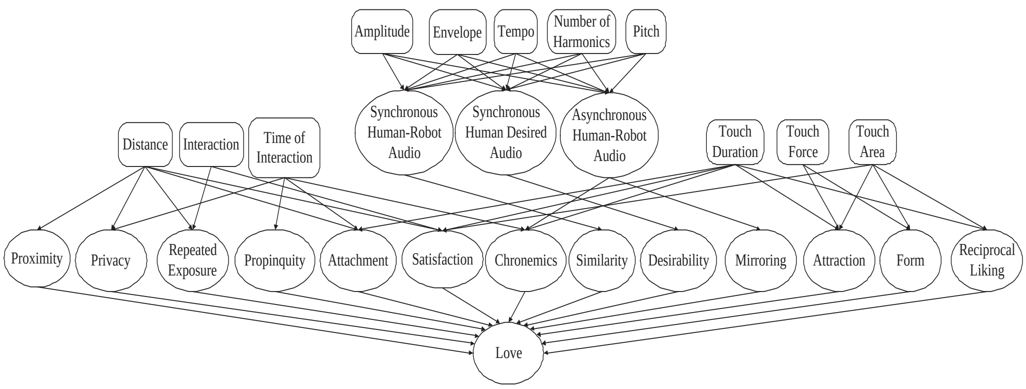

Figure 3.8: The overview of the Bayesian network for Probabilistic Love Assembly (PLA) module

- Synchronous and asynchronous audio parameters of the human and the robot,
- Duration, force, and area of the touch.

Above variables can be correlated with their conditional independencies via a directed acyclic graph to generate a probabilistic model that consists of location, audio and touch variables as system inputs, 13 causes of love as intermediate events and overall love probability as the outcome of the Bayesian network.

Artificial Endocrine System (AES) Hormones which are related to emotions and biological qualities according to the human endocrine system [185, 71] are utilized in AES module of Lovotics.
Artificial emotional hormones, which include Dopamine, Serotonin, Endorphin, and Oxytocin, are closely related to human emotions and presented in Table 3.4. For biological hormones Melatonin, Norepinephrine, Epinephrine, Orexin, Ghrelin and Leptin hormones are employed which modulate biological parameters such as blood glucose, body temperature, and appetite. Biological hormones and their effect of AES module are presented in Table 3.5.

The level of emotional and biological hormones can be considered as internal variables of the artificial endocrine system. This system in nonlinear and can be expressed in the form of first-order differential equations as below:

$$\begin{aligned} \dot{x}_t &= f_{(x_{(t)}, u_{(t)})} \\ y_{(t)} &= h_{(x_{(t)}, y_{(t)})} \end{aligned} \tag{3.32}$$

Table 3.4: Emotional Hormones

Hormone	**Effects**	**Virtual function**
Dopamine	Excitement, Alertness	Activity
Serotonin	Happiness, Tension	Happiness
Endorpin	Sense of Well-Being	Contentment
Oxytocin	Trust, Empathy, Love	Love

Table 3.5: Biological Hormones

Hormone	**Effects/Action**	**Virtual**
Melatonin	Drowsiness	Drowsy, Sleepy
Norepinephrine	Blood pressure	Excited, Active
Epinephrine	Blood Glucose	Agile
Orexin	Heart Beat Rate	Stimulated, Motivated
Ghrelin	Appetite	Hungry, Dizzy
Leptin	Metabolism	Lazy, Listless

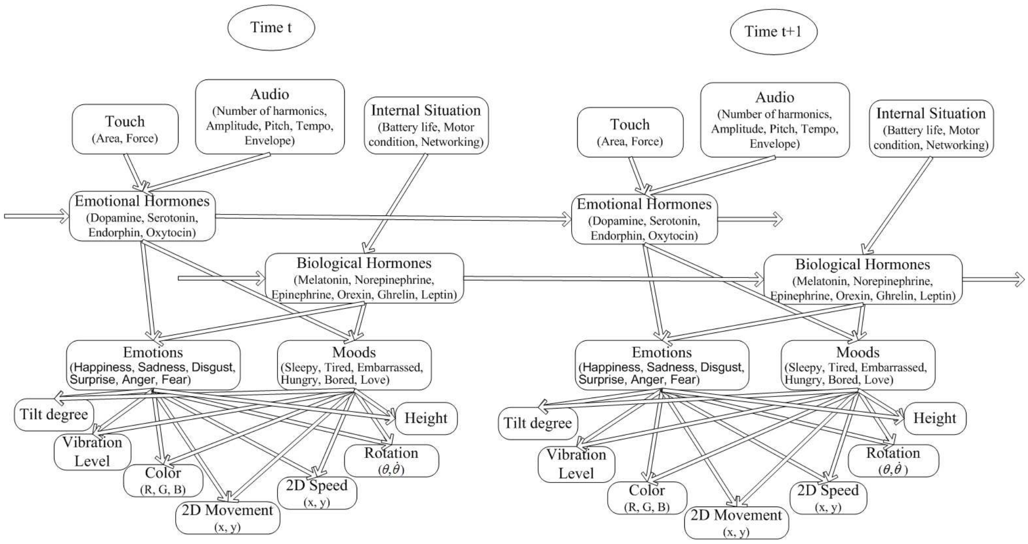

Figure 3.9: Dynamic Bayesian Network of Lovotics

where $u \in \Re^{v_1}$, v_1= is number of input variables which includes touch area, touch force, number of harmonics, amplitude, pitch, tempo, envelope, battery charge, motor situation, and network situation,
$y \in \Re^{v_2}$, v_2= is number of output variables which includes tilt degree, vibration level, color values, position parameters , speed parameters, rotation parameters and height,
$x \in \Re^{v_3}$, v_3= is number of endocrine state variables which includes Dopamine, Serotonin, Endorphin, Oxytocin, Melatonin, Norepinephrine, Epinephrine, Orexin, Ghrelin and Leptin,
and $f_{(.)}$ and $h_{(.)}$ are vector-valued nonlinear functions.
The above nonlinear artificial endocrine system can be managed through the use of a Dynamic Bayesian Network (DBN) [169, 94]. There are four major layers in the DBN system, namely input, endocrine, emotional and behavioral layers. In the input layer, touch and audio are the two main preceptors with their respective parameters. In addition, internal situations of the robot such as battery life, motor conditions and networking situations are considered to regulate the biological hormones. The endocrine layer consists of emotional and biological hormones. In the emotional layer six basic emotions and six moods are used to model the emotional situation. In the behavioral layer, tilt degree, vibration level, color, 2D movement, 2D speed, rotation and height are output parameters of the robot. Lovotics DBN is illustrated in Figure 3.9.

Affective State Transition (AST) The main two dimensions of emotion are considered as Activation ($\vec{Act}$) and Motivation ($\vec{Mot}$) axes in the two dimentional affective state plane in order to develop a affective space. The third dimension

of this affective space is also considered to represent Sub-States via the $\vec{Sub}$ axis. This third axis is used to present rate of changes in the main two dimensions. Hence, the affective space of the robot is defined as a three dimensional Cartesian coordinate system with axes: $[\vec{Act}, \vec{Mot}, \vec{Sub}]$.
Using the above affective space, a novel transition system is proposed which could handle the immediate emotional properties of the robot. This short-term emotional module cooperates with the two other AI modules of Lovotics robot to manage overall internal state of the robot.
In order to model the system to link interaction and affective states, the transition in the affective state space is formulated as below:

$$\vec{S}_{t_{Act,Mot,Sub}} = \vec{S}_{t-h} + \eta\vec{\Phi} + \beta\Gamma\vec{\Delta} \tag{3.33}$$

where $\vec{S}_t$ is the affective state of the robot in the affective space at time t and $\vec{S}_{t-h}$ is affective state in time $t-h$, where h is the sampling time.
$\vec{\Phi}$ is the vector field over the states which converges to a stable point in affective state coordinate system.
Vector $\vec{\Phi}$ can be considered as the gravitational field of a point mass c, located at point $r_1 \in \Re^3$ having position $r_0 \in \Re^3$ as:

$$\vec{\Phi} = \frac{-kc}{|\vec{r} - \vec{r}_0|}(\vec{r} - \vec{r}_0) \tag{3.34}$$

where $c, k \in \Re$ are constant numbers, $\vec{r}, \vec{r}_0 \in \Re^3$, $\vec{\Phi}$ points toward the point r_0 and has magnitude $|\Phi| = \frac{kc}{|\vec{r}-\vec{r}_0|^2}$.
η is the adjusting parameter for converging vector field.
β is the affective state coefficient which can be assigned to regulate rate of changes in the affective state.
Γ is the learning rate.
$\vec{\Delta} = \vec{\Delta}_{Act,Mot,Sub}$ is the three dimentional normal vector to transfer the state over time in the affective state space based on the emotional input according to interactions.
First two components are in the Activation - Motivation plane which are driven from emotional input:

$$\vec{\Delta}_{Act,Mot} = \sum_{m=1}^{6} e_{Mot_m}\vec{Mot} + \sum_{m=1}^{6} e_{Act_m}\vec{Act} \tag{3.35}$$

where $\vec{Mot}$ and $\vec{Act}$ are representation of Motivation and Activation axes in X and Y directions in Cartesian coordinate system and vector e corresponds to the six values of the basic emotions, which are happiness, sadness, disgust, surprise, anger and fear, in Activation and Motivation directions.

The third component of $\vec{\Delta}$ represents the movement in the sub-state direction which obtained from the rate of the first two components:

$$\vec{\Delta}_{Sub} = |\frac{d}{dt}\vec{\Delta}_{Act,Mot}|\vec{Sub} \tag{3.36}$$

where $\vec{Sub}$ is the representation of the sub-states axes in Z direction in the Cartesian coordinate system. In this way the vector $\beta\Gamma\vec{\Delta}$ finds its direction to reach the next affective state.
Hence the overall affective state formula, considering the interaction and transition methodology, can be presented as:

$$\begin{aligned}\vec{S}_{t_{(Act,Mot,Sub)}} = \vec{S}_{t-h} + \eta\frac{kc}{|\vec{r}-\vec{r}_0|^2} + \beta\Gamma(\sum_{m=1}^{6} e_{mot_m}\vec{Mot} \\ + \sum_{m=1}^{6} e_{act_m}\vec{Act} + |\frac{d}{dt}\Delta_{Act,Mot}|\vec{Sub})\end{aligned} \tag{3.37}$$

In this way, the short-term affective state of the robot can be generated for computing the immediate sentimental properties of the robot. Using this short-term affective property, the robot is capable of undergoing several affective states by employing the Affective State Transition module which handles transformations from one affective state to another. As presented, these transitions are based on previous states, current mood, and interaction influences from the environment.

3.1.2.3 Behaviors

In order to find effective parameters for Lovotics behavior, as presented in 3.1.2.2, initially an extensive research was made on the human non-verbal behavioral patterns that can promote positive feelings and a level of intimacy between humans and robots. Then behaviors of the robot were designed based on that research according to Table 3.6.
The reason for mapping human behaviors into the context of Lovotics is to provide the robot with a consistent human-like quality such that humans would feel more comfortable around it.

Input received from the various sensors are fed through the Artificial Intelligence layer, which then controls the Behavioral Planner layer for various outputs according to Figure 3.10

Audio ouput As presented in 3.1.2.2 it has been found that there are a number of paralanguage parameters that can categorize emotional states effectively . Based on that, it is investigated that how a robot could generate positive feelings, and through these positive feelings such as attachment and liking, promote the feeling of love. When interacting with a human, the robot performs the following paralanguage adjustments to promote positive emotions:

Table 3.6: Mapping Non-verbal Behaviors to Lovotics Behaviors

Non-verbal Behavior	Hardware	Output
Paralanguage	Speaker	Pitch and volume
Gesture	Tilt/height servo	Initiated skin deformation
Posture	Wheel motors	Body position and configuration
Haptics	Wheel motors	Rotation, navigation and movement to touch user
Proxemics	Wheel motors	Rotation, navigation and movement to follow/avoid user in accordance to user position
Chronemics	Wheel motors, speaker, RGB LED, tilt/height servo	Rate of variation of rotation, navigation, pitch, volume, color, brightness and skin deformation
Facial Expressions	RGB LED, tilt/height servo	LED blinking, color, brightness and skin deformation
Synchrony	Wheel motors and tilt/height servo	Rotation, Navigation and skin deformation in time with user's inputs

1. **Lowering the number of harmonics, that is, having a low filter cutoff.** By increasing the filter cutoff level from a technical perspective, that is, by conserving higher number of harmonics from a natural perspective, one is more prone to the feelings of potency, anger, disgust, and surprise, while if the filter cutoff level is low, meaning a lower number of harmonics, an individual would then experience feelings associated with pleasantness and happiness.

2. **Reducing the amount of amplitude variation:** Smaller variations in amplitude can convey feelings of happiness and pleasantness, while larger variations are mainly associated with the feeling of fear.

3. **Lowering pitch levels, larger pitch variations and low regions of pitch contours.** Pitch contains certain parameters which, after manipulation, allow to control and generate affective states that would result in different

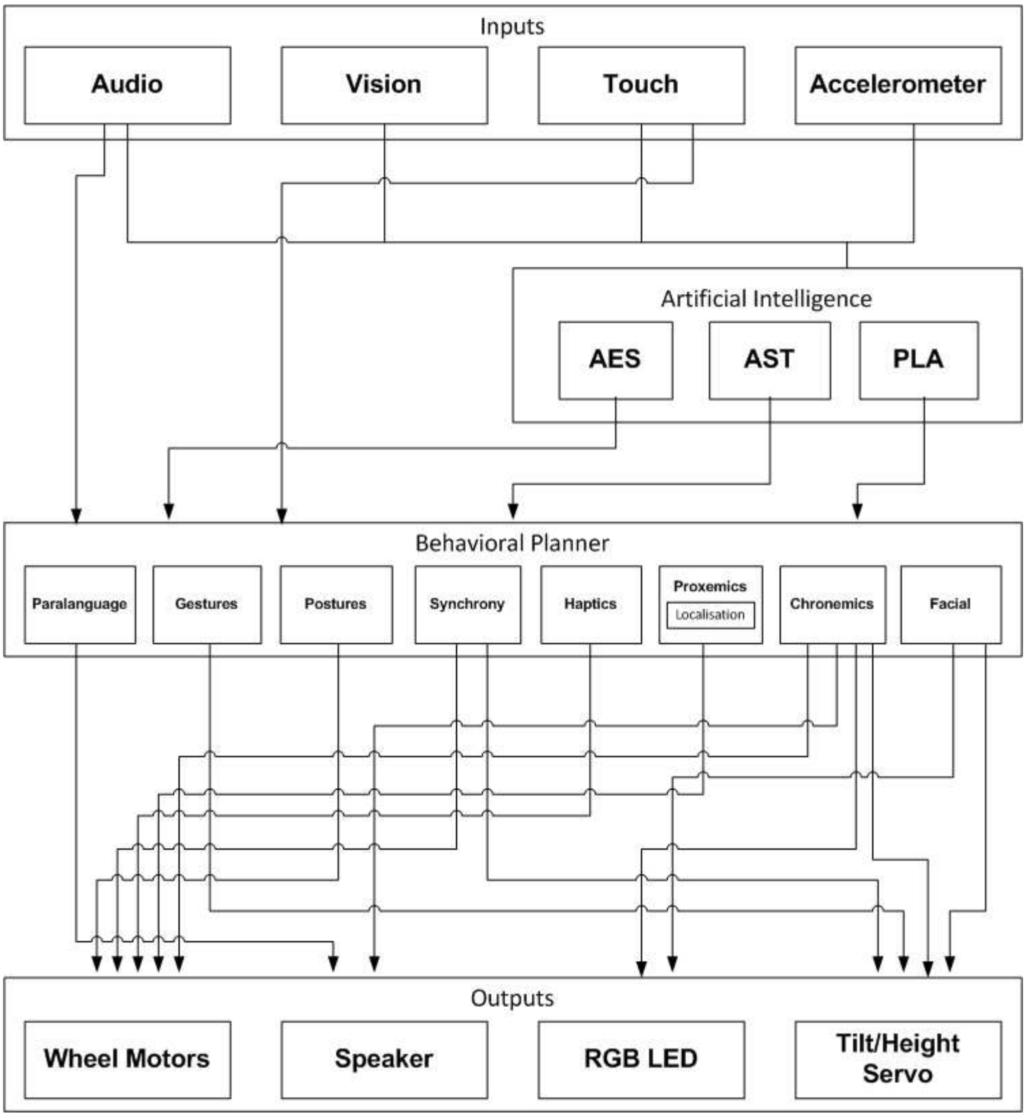

Figure 3.10: Behavioral planner of Lovotics robot and it's association with inputs, AI, and outputs

perceived emotions. Lower pitch levels, larger pitch variations, and low regions of pitch contours correspond to feelings of happiness, surprise and pleasantness.

4. **Increasing tempos in the generated sound.** A slow tempo or a slower pace is often associated to feelings of sadness, boredom and disgust, while a faster tempo corresponds to feelings of surprise, happiness, fear, and anger. Tempo is one of the main paralanguage parameters that have a very obvious impact on human emotional states.

5. **Sharpening sound envelopes.** A sharper envelope conveys feelings of surprise, happiness, pleasantness, and activity while a more rounded envelope would generate audio that invokes the feelings of disgust, sadness, fear, and boredom.

Furthermore, as an optional design feature, different emotional features are also able to be generated through the variation of the five paralanguage parameters shown earlier. Listed next are a few emotions and the necessary paralanguage adjustments needed to achieve the effect [209, 30].

- Anger: large number of harmonics, high pitch levels, fast tempo, small pitch variation.
- Boredom: slow tempo, low pitch, few harmonics, round envelope, pitch contour down.
- Sadness: slow tempo, low pitch level, few harmonics, round envelope.
- Fear: pitch contour up, many harmonics, high pitch level, round envelope.

Based on the non-verbal behaviors study, in addition to the paralanguage parameters, three additional audio related parameters were identified that are non-verbal behavioral factors and are mapped into the realm of audio. These parameters are chronemics, proximity and synchrony. Through Lovotics research, the validity and usability of these factors were tested in a real interaction scenario and identify which ones have concrete implementation value and functionality that can be used within the audio system of Lovotics robot.
The three parameters are elaborated below:

1. **Chronemics:** The effect of sound duration is utilized in audio interaction to promote feelings of affection. By varying the length of robot audio response to 1 second, 3 seconds and, 5 seconds respectively [78, 214], our goal was to measure the human response with regards to duration of the audio interaction, thus aiming to create a lifelike and pleasant interaction between human and robot.

2. **Proximity:** The distance between the source of sound (robot) and the person it is interacting with also plays a role in affecting the relationship between robot and human [104]. Here, the effects of physical distance were mapped over into audio, with the aim of using audio proximity to emulate the effects of physical distance. The chosen distances were 0.4 meter, 1.0 meter, and 2.0 meters to represent close, moderate and far distance respectively. These three numbers have been chosen based on Intimate, personal, interpersonal and public distances [105].

3. Synchrony Synchrony in this case refers to matching the audio parameters of the robot with that of the participant. In the case of interaction between humans and robots, pitch synchrony can be a source of attraction between them. It is associated to the fact that a person attracted to someone he or she is conversing or interacting with, will stand closer to them and don't mind entering their personal space or letting the other person enter his or her own personal space. On the other hand if someone is not attracted to the person he or she is conversing with, the personal space becomes bigger and the person that enters that space will be given clues by the other to back off or he himself backs off.

Thus, the effect of synchrony was measured with respect to one audio parameter, which in our case is pitch. We achieved this by using an audio software to capture the real-time pitch variation of the test user, and synchronize our audio output's pitch level. The synchrony level would be adjusted to synchronized audio as well as anti-synchronized audio levels.

With the purpose of testing and researching whether synthesized audio samples generated by the Lovotics audio system have any effect on enhancing attachment between robots and humans, a user test was conducted which tested users on their response to our audio system. The purpose of the user-test session was to gauge the likability and the level of appeal of the Lovotics audio interface and to determine the success of the audio samples from the users' perspective. Following issues were being considered:
Do users complete each interaction successfully? If so, how effective was the interaction? Where do they stumble? What problems do they have? Where do they get confused? What non-verbal cues or audio were they looking for which were missing?
The preceding work leads to formulate two research questions:
R1: What role does variation in chronemics, proximity and synchronization play on enhancing attachment between humans and robots?
R2: What is the effect of these factors both individually and mutually?
For the purpose of rigorous testing, all the possibilities and combinations of the following three factors were examined and obtained user responses on the effect of these factors on the sound generated.

1. Chronemics variations (1, 3 and 5 seconds)

2. Proximity variations (0.4, 1 and 2 meters)

3. Synchrony variations (synchronization and anti-synchronization)

In total 18 different interactions exists in this case (18 different audio responses) to test on the 36 participants. It comes from 3 for chronemics, 3 for proximity and 2 for synchrony which makes $3 \times 3 \times 2$ trials. These sounds were presented in a counterbalanced order to all participants, to avoid associative effects. Different trials for this user study are presented in Table 3.7.

Participants were asked to rate these different interactions on a scale of $1 - 10$

Table 3.7: Different Trials Tested upon the Users

	Chronemics		
Proximity	1 second	3 second	5 second
0.4 meter	1,2	7,8	13,14
1.0 meters	3,4	9,10	15,16
2.0 meters	5,6	11,12	17,18

Synchrony: All odd numbered trials
Anti-Synchrony: All even numbered trials

on the basis of `likability´as well as `positivity´felt during the interaction. Other key factors that were noted during the interaction process were:

- How fast the users orientate themselves to the situation of interacting with a robotic audio system;
- If there are any signs of self conscious or nervous behavior;
- User's verbal comments and feedback regarding the whole interaction process.

3.2 Evaluation

The Lovotics Love Attitude Scale (LLAS) is an adaptation of Love Attitude Scale (LAS) from human - human love to human - robot love. The key issues of LAS which decide the love style of human were studied and were mapped to the Lovotics aspect for developing a similar love response for human - robot love. The LLAS also gives us the love style of a person similar to LAS, but with respect to human - robot love. The six ``colors of love´´ or ``love styles´´ as proposed by John Lee, then continuously researched by Hendrick [114] are mapped from human - human love to human - robot love for Lovotics. Results are shown in Table 3.8.

During the study, the users are requested to interact with the robot. They are then asked to answer a questionnaire based on their interaction with the robot. The questionnaire for LLAS is adapted from short form of LAS and presented in Table 3.9.

Table 3.8: Love Styles for Lovotics

Love Style	Definition	Key issue	Lovotics Aspect
Eros	Sentimental and intuitive physical attraction	Physical	Aesthetic
Ludus	Enjoyment of the fun of playing	Playfulness	Behaviors
Storge	Affection that slowly develops from companionship	Friendship	Interaction
Pragma	Finding desired attributes rationally	Logic	Artificial Intelligence
Mania	Volatile and obsessive need	Need	Ownership
Agape	Selfless altruistic and sacrificial devotion	Care giving	Nurture

Table 3.9: LLAS: Lovotics Love Attitude Scale. Adapted from short Love Attitude Scale (LAS) from human-human to Human-robot.

No.	**Lovotics Human to Robot Love Attitude Scale**	**Lovotics Robot to Human Love Attitude Scale**
Eros		
1	I feel that I have chemistry with the robot.	I feel that the robot has chemistry with me.
2	I was attracted to the robot immediately after I first met the robot.	The robot was attracted to me immediately after first met me.
3	I was emotionally involved with the robot rather quickly.	The robot was emotionally involved with me rather quickly.
4	The robot fits my standards of physical beauty.	The robot seems to like my appearance.
Ludus		
5	What I don't know about the robot won't hurt me.	What the robot doesn't know about me won't hurt it.
6	I could get over my affair with the robot pretty easily and quickly.	The robot could get over its affair with me pretty easily and quickly.

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Table 3.9 – Continued

No.	Lovotics Human to Robot Love Attitude Scale	Lovotics Robot to Human Love Attitude Scale
7	I would get upset if I knew of some of the things robot have done with other people.	I think that the robot would get upset if it knew of some of the things I've done with other people.
8	When the robot gets too dependent on me, I want to back off a little.	When I get too dependent on robot, it backs off a little.
Storge		
9	My love towards the robot grew out of a long friendship.	The robot's love towards me grew out of a long friendship.
10	I like the robot.	The robot likes me.
11	The robot is my friend.	I know myself as a friend of the robot.
12	I care about the robot.	The robot cares about me.
Pragma		
13	The reason that I am attracted to this robot is that the robot is useful for me	The reason that the robot is attracted to me is that I am useful for it.
14	Logically I think that the robot is lovable.	The robot loves me because of it's artificial intelligence
15	I see my desired parameters of a good partner in this robot.	The robot finds its desired parameters of a good partner in me.
16	I love this robot by my head instead of heart.	The robot loves me because of it's computer programmes.
Mania		
17	When the robot doesn't pay attention to me, I feel sick all over.	When I don't pay attention to the robot, it will get crazy.
18	Since I've been in love with this robot I've had trouble concentrating on anything else.	The robot is so in love with me that it cannot do anything else.
19	I cannot relax if I suspect that my robot is with someone else.	The robot cannot relax if it suspects that I am with someone else.

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Table 3.9 – Continued

No.	Lovotics Human to Robot Love Attitude Scale	Lovotics Robot to Human Love Attitude Scale
20	If the robot ignores me for a while, I sometimes do stupid things to try to get it's attention back.	If I ignore the robot for a while, it sometimes do stupid things to try to get my attention back.
Agape		
21	I would rather suffer myself than let the robot suffer.	The robot rather suffer itself than let me suffer.
22	I cannot be happy unless I place the robot's happiness before my own.	The robot cannot be happy unless it places my happiness before its own.
23	I am usually willing to sacrifice my own wishes to let the robot achieve its.	The robot is usually willing to sacrifice its own wishes to let me achieve mine.
24	I would endure all things for the sake of this robot.	The robot would endure all things for the sake of me.

Table 3.10: Love Scales for the LLAS

User's response	Love scale
Strongly Disagree	0
Moderately Disagree	0.25
Neutral	0.50
Moderately Agree	0.75
Strongly Agree	1

Human - robot love for Lovotics is proposed to be considered as three different cases: Human-to-robot love ($Human \rightarrow Robot$), robot-to-human love ($Robot \rightarrow Human$) and bi-directional human-robot love ($Human \leftrightarrow Robot$).
To implement Lovotics Love Attitude Scale (LLAS) for evaluating the two main parameters (human to robot love ($Human \rightarrow Robot$) and robot to human love ($Robot \rightarrow Human$)), the users are asked to answer 48 questions (2 parameters $\times$ 6 styles $\times$ 4 items), using the response that indicated how much they agree or disagree with that statement: (1) Strongly disagree, (2) Moderately disagree, (3) Neutral- neither agree or disagree, (4) Moderately agree, and (5) Strongly agree. Based on the user responses the mean value of all six love styles are measured, for both human to robot love and robot to human love in scale of $0 - 1$.

The mapping of these two ranges is presented in Table 3.10. Human-robot love (*Human* $\leftrightarrow$ *Robot*) can be calculated using (*Human* $\rightarrow$ *Robot*) and (*Robot* $\rightarrow$ *Human*).

Chapter 4

Results

4.1 Simulation

For initial testing of algorithms and to visualize interactions of Lovotics, a simulator program is developed for Lovotics. This simulator includes a virtual model of the robot, humans and the corresponding interactions within the environment. The main interface of the simulator is presented in Figure 4.1.
In Lovotics simulator a robot is placed between several humans and left to interact with them. During interaction in the environment, the levels of six biological and four emotional hormones change accordingly. Furthermore, probability of love between the robot and different interactants are being calculated dynamically in PLA module as illustrated in the simulation environment in Figure 4.1.
Figure 4.2 shows how affective state of the robot and probability of love were changing during interaction. Values of activation, motivation, and sub-state were changing during the interaction and probability of love between the robot and certain human was increased during two hours of interaction in the simulator. After series of try and error, several parameters were tuned in the simulator in order to increase the probability of love as the user spends more time with the robot. The relationship between tuned parameters in the simulator has been adopted later for the real robot calibration.
As another usage of the simulator, instantaneous changes in main parameters of PLA module during a ten minute interaction in the simulator is presented in Figure 4.3 simultaneously. Proximity, repeated exposure, attachment, similarity, and attraction parameters have changed based on the interaction values to form the overall intimacy between robot and human.
The simulator was employed in this stage of Lovotics software design in order to examine, improve, and verify proposed PLA module of the Lovotics artificial intelligence. Final PLA module of the Lovotics robot was equipped with non-

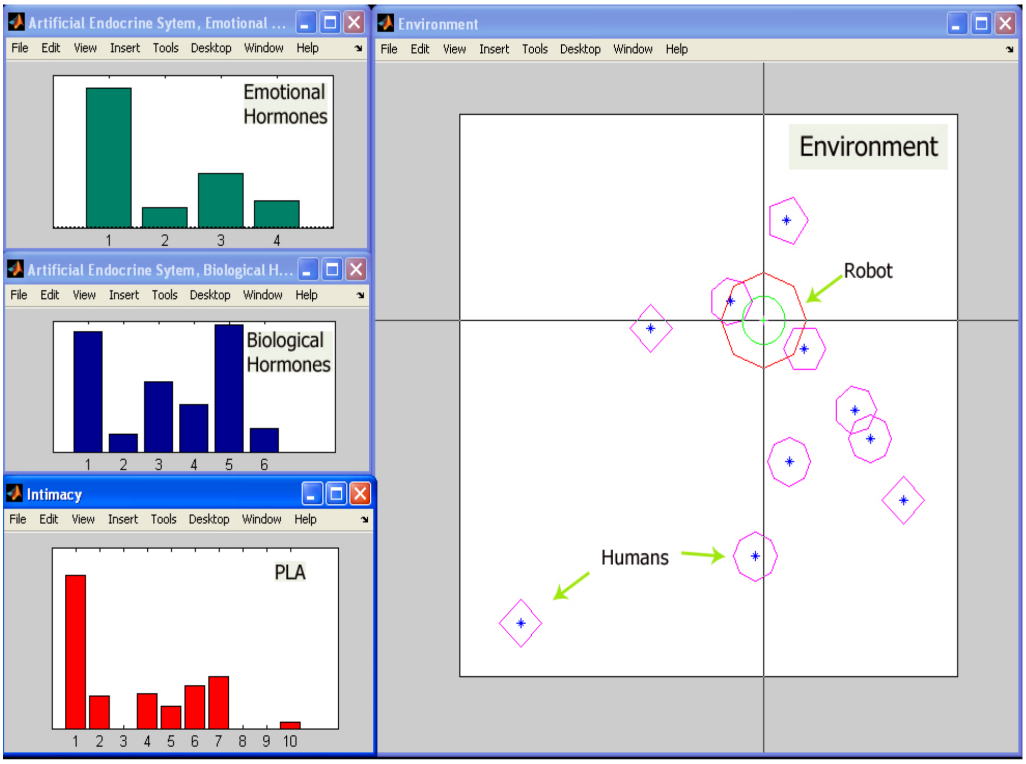

Figure 4.1: Lovotics simulator. Right: Simulated model of robot's environment. Left (from top) Emotional and biological hormones levels and probablity of love between the robot and humans in the environment.

instantaneous system with more parameters in the form of a Bayesian network as presented in 3.1.2.2.

4.2 Developed robot

Based on the proposed methods, a robot was successfully designed and developed as an affective agent in social interactions to inculcate love with humans. Throughout Lovotics development, hardware and software modules were built, improved, and integrated by piecing together a fully functional robot capable of utilizing a camera for vision, touch sensors for feedback, RGB LEDs for light color signals, speakers for audio output, microphone for audio input, an Arduino controller controlling gesture servo motors, lights and accelerometer motion feedback, and an independently controllable wheel motor system.
The Lovotics hardware was integrated with fully functional software system to detect and process sensory values, process data, and finally command appropriate outputs to actuators.

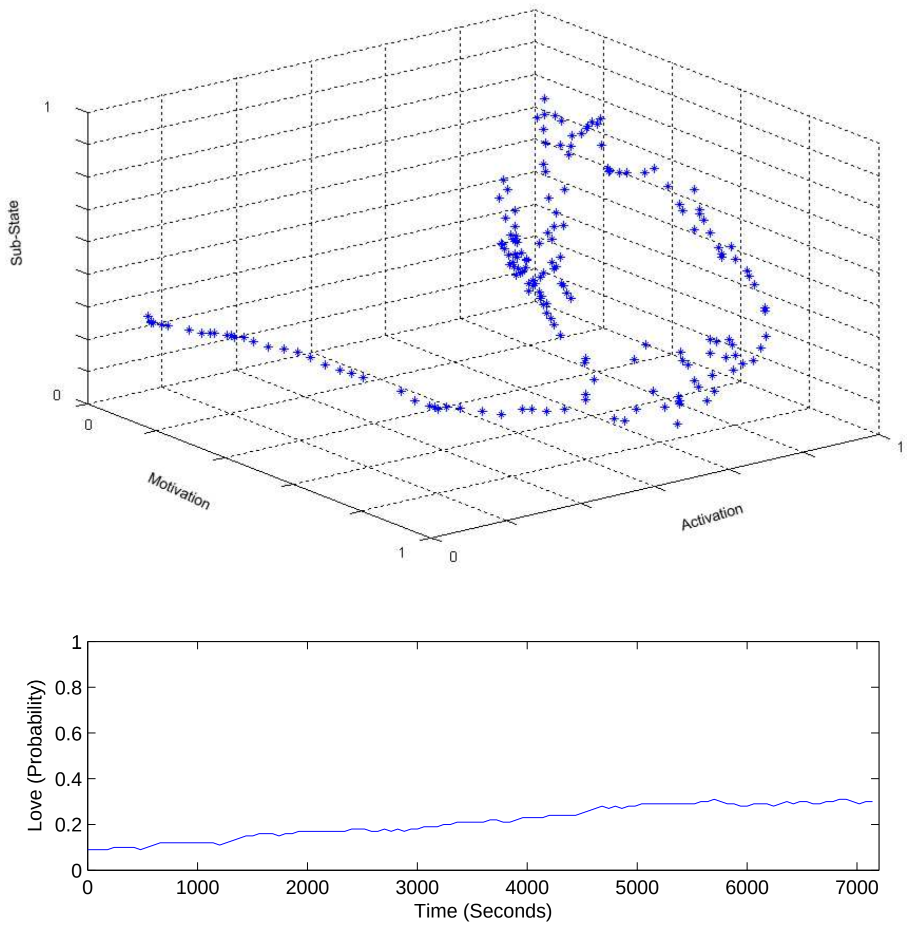

Figure 4.2: Changes in AES (top) and PLA (bottom) modules of the robot during interaction in Lovotics simulator.

4.2.1 Final robot

The process of design for Lovotics robot is illustrated in Figure 4.4 and different versions of Lovotics robot hardware implementation is presented in Figure 4.5. To achieve the final form and functionality 10 generations of robot were designed and developed.*

*Several undergraduate students, interns, research engineers, and designers have collaborated for design and developments of hardware and software of 10 versions for Lovotics robot. Details of implementations are available in final year project reports of involved undergraduate students. Versions 1 to 4 [172], 5 and 6 [55], and 7 to 10 [148], audio interface [79], vision interface [182], and artificial intelligence implementation [191] were sub-projects of Lovotics implementation.

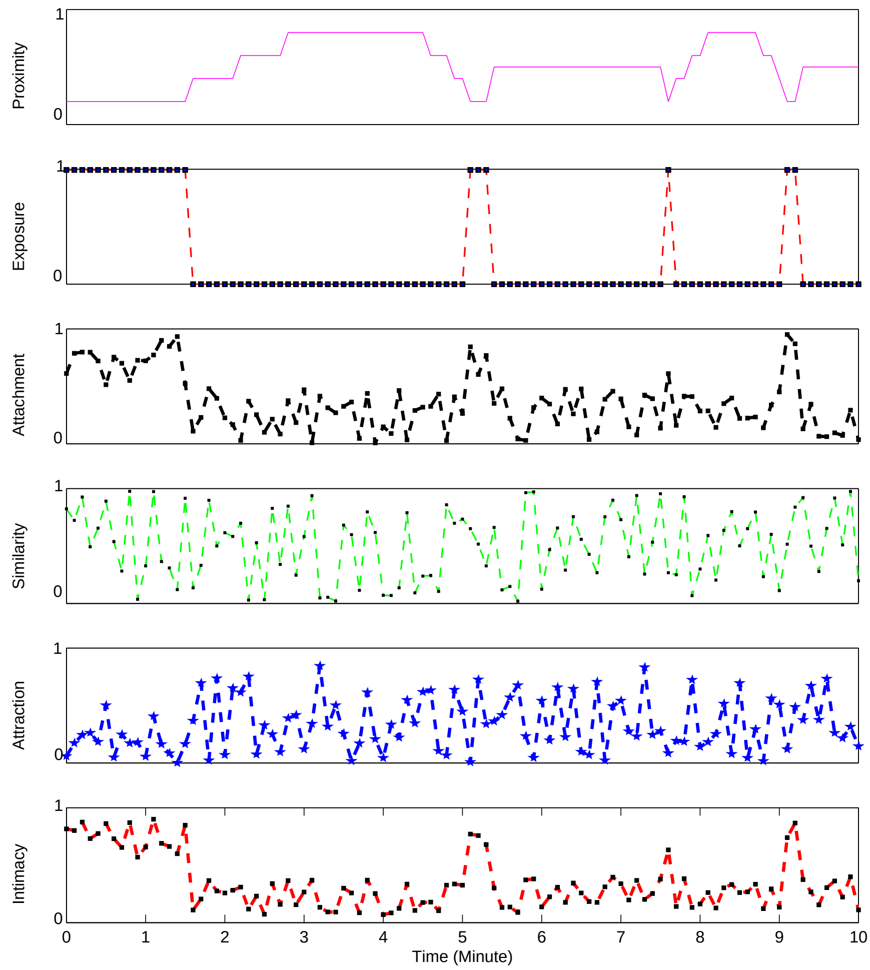

Figure 4.3: Normalized values of love variables during 10 minutes of human-robot interaction in Lovotics Simulator

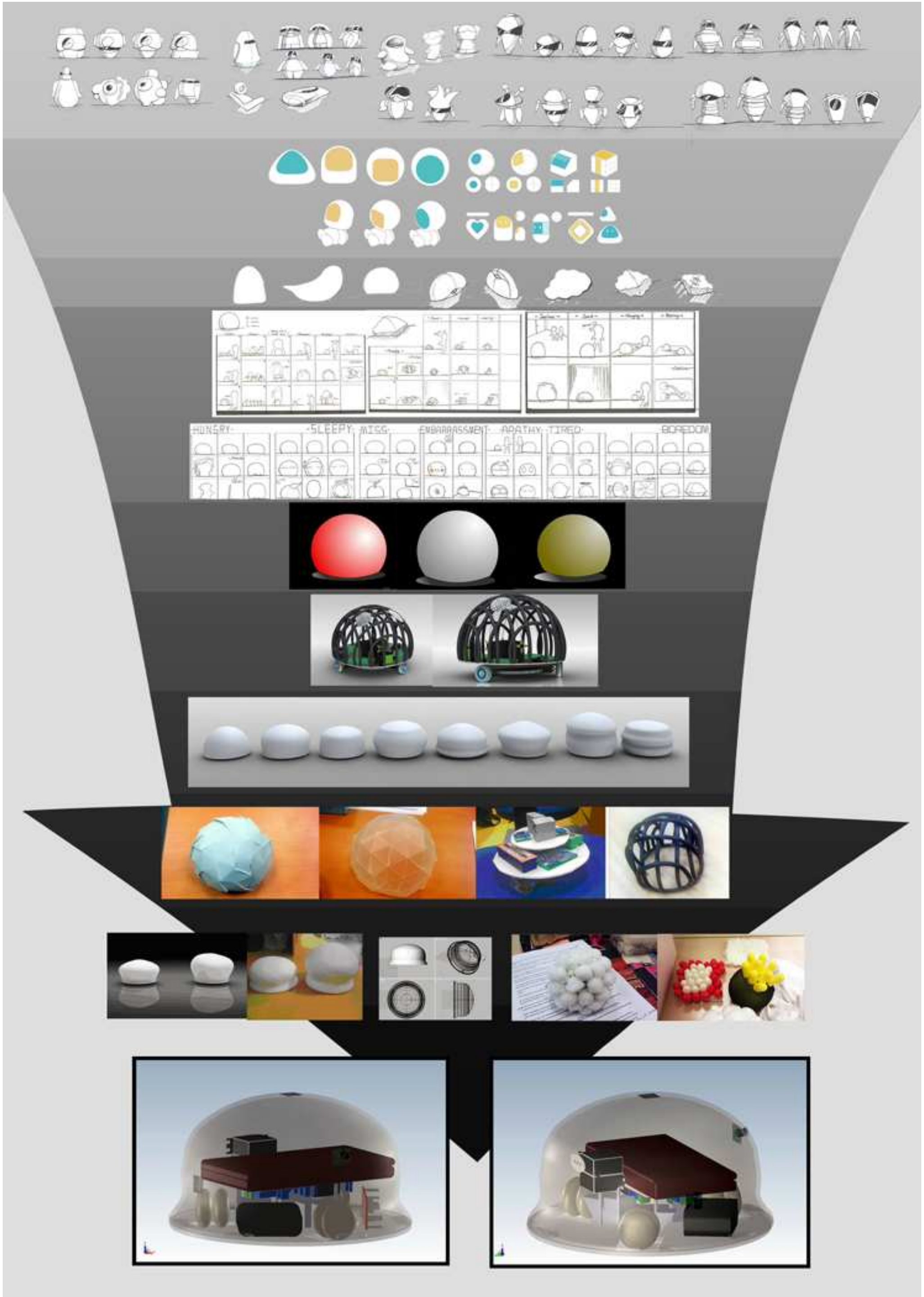

Figure 4.4: Design process for Lovotics robot.

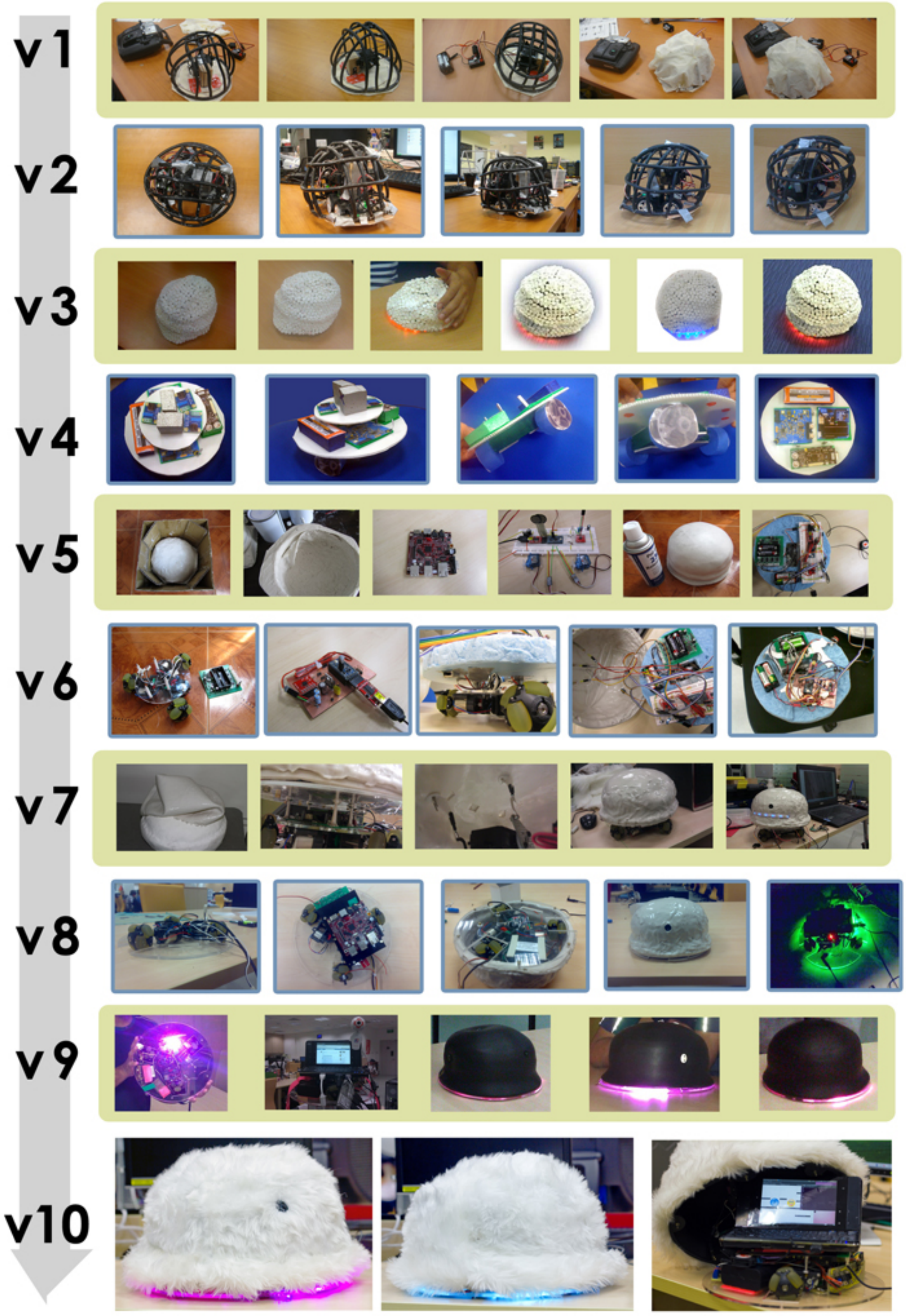

Figure 4.5: Different versions of Lovotics robot hardware implementation.

- **Version 1:** According to the designed explained in previous Chapter in 3.1.1.6, servo motors were employed in the first version of Lovotics robot to actuate a vertical and tilting movement by virtue of applying force on its flexible endoskeleton design. Considering the designed semi-egg shape of the robot, height modulation and tilting movements were employed to imitate postural movement. In fact, quick height modulation periodically could depict a sort of breathing movement. Servo motors along with attachments were actuators for height modulation and tilting functions in the robot.
  To implement the egg shape of the robot, a lattice dome shaped grid structure was developed. Poly vinyl foam material was used for building such structure. The grid provided points where force could be applied and this could be used to provide height modulation and tilting.
  The first version of the robot was not mobile but it has been used for investigating possibilities of deformation for expression.

- **Version 2:** The final developed flexible structure in version 1 was mounted on top of a four wheeled mobile platform to generate the second version of the Lovotics robot. In this way, the robot was able to express basic behaviors and motions.

- **Version 3:** After testing several materials, the mobile platform with flexible semi-egg shape body was covered with white surface in version 3. LEDs were placed under the white cover. In this way, the first generation of robot was formed which could fulfill basic design requirements including mobility, flexible body, and attractive outline.

- **Version 4:** Dimensions of the components were important challenge due to size constraints of the robot in addition to functional;ities. Hence a paper model was constructed as version 4 to verify their compatibility in arrangment. Various types of sensors, processors, and actuators were examined and arrangement of those module were modeled in this version to find out a suitable platform for interior structure of the robot.

- **Version 5:** To implement the semi-egg shape outer part of the robot, after making several prototypes, silicon material was used in version 5. The material is flexible and capable of returning to its original shape in the absence of actuator force. As observed by this research and resulting design, posture of the robot is essential in developing affective expression.
  A Beagleboard [47] was used as the main software processor of the robot.

By utilizing standard interfaces, the Beagleboard is highly extensible to add many features and interfaces but it is not intended for use in end products. In version 5, initial testing for using silicon cover, Beagleboard and sensors were performed in order to prepare modules for next integrated versions. The OMAP 3530 on Beagleboard was the central processing unit of Lovotics. It took data inputs from Arduino, processed major artificial intelligence programs to generate corresponding commands which were sent back to Arduino or motor-base CPU. There was Linux Ubuntu system installed to facilitate fast processing speed without much occupation of system resources.
The audio connector and embedded sound processing card enabled direct interfacing between CPU and sound input. Thus Lovotics was capable of detecting and recognizing human voice as long as a speaker is plugged in. The LCD connector was capable of transmitting data between CPU and a LCD monitor. Once connected, the image of Ubuntu system was displayed on the screen. User could have access to a GUI application which displays all input information, output information and interim processing data.
Either the power connector or the OTG port is capable of powering up Beagleboard. The difference is the power connector accepts voltage higher than 5V. since there is on-board voltage regulator while the OTG port accepts an exact voltage of 5V.
The SD connector hosted a SD card on which the Ubuntu system was installed. This SD card also functioned as hard disc of computer and stored all files. The system automatically booted from SD card upon switched on by default.

- **Version 6:** Since patterns of Lovotics motion needed to depict affective expression, it was decided to design a holonomic structure for the robots motions. To achieve this motion, omni wheels were used for the base of the robot. Translational and rotational motion was realized with an omni directional mobile base. A holonomic robot can instantaneously move in any direction. It does not need to do any complex motions to achieve a particular heading. This type of robot would have two degrees of freedom in that it can move in both the X and Y plane freely. The control of this omni wheel base is managed via a PID controller and different patterns of movement indicate different expressions.
  Accelerometer sent the acceleration data on X, Y and Z axes respectively to Arduino. Arduino used these information to calculate instant displacement in these three directions. Subsequently the rough localization information could be obtained given the initial position.
  Three force sensing resistors were integrated on Lovotics cover. The main

use of FSRs was to enable Lovotics to feel various degrees of human touch, thus generate corresponding robotic behavior and interact with human more effectively. The interfacing module between FSR and Beagleboard CPU was Arduino. It collected voltage outputs from FSRs and translated them into corresponding force amount, then pass to Beagleboard CPU through USB cable.
The interfacing between the motor base and Beagleboard CPU was another PCB board on which a mini-CPU and several input/output ports were placed. This PCB board received the commands of Beagleboard CPU and generated corresponding signals to control the movement of motor base.
The RGB LED strip was also integrated under the robot. It was connected to the Beagleboard via the Arduino board in a same methods as other sensors and actuators.
The version 6 of the robot had a crudely home-made silicone cover which lacked an appealing aesthetic sense. The RGB LED lights were hard coded and void of any relation with the installed artificial intelligence.

- **Version 7:** For version 7 of the hardware, the unreliable hard foam as base structure of the robot in version 6 was replaced with a precision laser cut acrylic platform which was 6mm thick. Metal stilts were added to the motor platform below for an elevated design.
RGB LED strips were lined through the silicone skin and connected to the Arduino board. A hole was cut in the cover to insert the camera lens. A dual servo, triple metal latch design was used to replace the previous wire tugged design to create large gesture movements in the skin.
The main problem of version 7 was that omni directional wheels were completely visible under the silicon cover.

- **Version 8:** In version 8, the original acrylic base which was mounted on top of the omni directional wheels was inverted and placed a couple millimeters above ground. This was achieved by screwing the base to the omni directional wheel gearboxes and the larger diameter of the wheels lifted the platform off the ground by a small distance. With this design, the hardware components were all easily concealed within the silicone skin itself, thus improving the aesthetics. An elevated platform mounted within the skin cover itself to house the Arduino PCB and the Beagleboard which contained the Lovotics artificial intelligence.
The prior LED strips were all removed and replaced with a single high-powered 3W RGB LED. The new LED provided enough light to diffract

through the acrylic base to create a glowing, hovering effect. However, in the process of adding the high powered LED, the previous usage of a 9V battery to power the gesture servos, the Beagleboard, and the LED could not sustain the system for a substantial amount of time. A Li-Ion battery pack rated at 5V/3mAh was used to power the output hardware instead.

- **Version 9:** By Version 9, it became apparent that the removal of the elevated platform design was causing space constraints within the robot cover. There was increasing difficulty in implementing new hardware within the confinement of the crudely made silicone skin, and wire management was becoming a significant design issue.
  A 3D model of a new and larger silicone skin were made and sent to a manufacturer for a commercially produced replacement for the old skin. The delivered product was a black colored skin made out of tough rubber. Rubber was used because the silicone material would not have been able to support the structure of the cover.
  The new toughness of the skin became too strong for the existing gesture servos to pull back and both servo motors melted down due to overheating. To counter this problem, two Futaba S9157 digital servo motors were used to handle the gestures. Rated at 30.6kg/cm torque at 6V, the servos were more than capable of handling the new problem. The new servo motors consumed more power than before, resulting in yet another change of the battery pack to a larger capacity option.
  A Fujitsu UMPC UH900 was also used to replace the Beagleboard for processing the artificial intelligence as the latter had evidently become way too volatile a platform to code on.
  Prototyping circuit boards used for power regulation and servo control were also turned into PCBs for less connection failure problems.

- **Version 10:** The final iteration of the robot prototype ends with version 10. It sports a white fur coat over an acrylic platform hovering slightly above ground and emits color signal lights. Final design of the robot is shown in Figures 4.6 and 4.7. Final robot is presented in Figure 4.9 and it's interior architect is shown in 4.8.
  After testing, the Fujitsu UMPC UH900 with Intel Atom Z530 1.6GHz CPU and 2 GB RAM was a clear winner to replace the Beagle Board. The Beagleboard was highly unstable and experiences frequent memory wipes just by slight voltage spikes, and that resulted in a large amount of time wasted on repeatedly reinstalling an entire operating system and its dependencies each time. With the UH900 the Ubuntu Lucid operating system runs much more stably and comes with its own rechargeable battery. An on-board

display and keyboard would also dramatically reduce the amount of time required to hook up the system to an additional peripherals as every component is self-contained. The existence of its own battery meant that the battery pack could now be used just to power the LED and servos, thus lengthening the operating time of the robot system.

The Arduino ProMini is a hardware selection back from version 6. It is still being used for processing inputs and outputs for the hardware components on the robot. By using serial data transfer, it functions as an actuation processor between the components and the artificial intelligence. The existing design of Arduino ProMini module from version 6 has proven to be robust and efficiently functional within a small area over 5 iterations of the robot, and therefore has never been replaced. The design also comes with an accelerometer on board.

Three omni directional wheels are each attached to a Tamiya High Power Gearbox configured to a gear ratio of 41.7:1. The three motors are connected to a microcontroller separate from the Arduino ProMini. The motor controller circuit is part of a robotics basic motor kit purchased from a company prior to version 6 of the Lovotics prototype. The wheel motor circuit is powered by 2 AA size batteries. The Arduino controls the movements of the motors by sending serial data signals to the separate microcontroller.

Two digital servo motors, Futaba S9157 , are used for actuating skin gestures for the robot. Each of the servo motors are rated at 30.6kg/cm torque and are used to handle three points of skin contact in providing deformation gestures. The pulling action is made possible by attaching the servo horn to the skin using a metal hook and latch, a technique commonly used for model helicopters.

A single web camera has been stripped down to its bare bones and attached to the skin cover, and plugged into the UMPC via USB. Using OpenCV libraries [31], images from the web camera is processed and used for face recognition in developing user behavior profiles.

The three force sensitive resistors as touch sensors were mounted on the surface of the robot and under the white cover to provide touch feedback from the user to the UMPC through the Arduino circuit.

The aim of the LED lights was to create colored signals that are emitted from the base of the robot, simulating a hovering effect. By combining an acrylic base and a high-powered LED, the effect was achieved. By using the PWM outputs on the Arduino circuit, 256 levels of light intensities can be achieved for each color channel, yielding a roughly 16.5 million possible color combinations.

To provide enough power to move the gesture servos and control the high-powered RGB LEDs for a substantial amount of time to carry out experi-

ments, a 5V/3000mAh Li-Ion battery pack was used in the system design. The original design involved a single low power 5V voltage regulator. The regulator was not able to handle the large amounts of current demanded by the LED and servos. As such, two high powered 5V RECOM voltage regulators rated at 1.0A current each were used to replace the original. The resulting circuit design is a high current rating 5V power supply from 4 separate connectors. This allows for easy powering of the LED and servos and makes space for any future hardware additions.
The RGB LED circuit schematic and the regulated power supply circuit was merged into a single space conserving PCB layout design and previewed in 3D simulation for space restriction checks. Since the design seemed flawless, it was fabricated and soldered.

4.2.1.1 Sensors

The robot is equipped with microphones and speakers for audio interaction with the environment and a camera for visual input. Also touch sensors are implemented on the surface of the robot for tactile interaction. All sensors are connected to the main processor where all computation is processed.

Audio An external microphone is connected to the main processor, which is a UH900 Fujitsu mini notebook, to capture the audio of the humans talking to the Lovotics robot. Open source softwares like Pyaudio [186], Numpy [56], and SoundAnalyse [256] are used to process the audio input.
Pyaudio is used to initialize the audio port on the system. The audio sample instance is then used to read in an audio sample from the microphone for a specific amount of time at a specific data rate. Pyaudio is also being used to play audio files on the UMPC using the same method of declaring an audio sample instance. Numpy is being used to convert the raw audio sample obtained as explained above into readable data for further analyzing. SoundAnalyse is being used to obtain the value of the loudness (amplitude) and pitch (frequency) of the audio input sample obtained as explained above.

Visual A single web camera has been stripped down to its bare bones and attached to the skin cover, and plugged into the UMPC via USB. Using OpenCV libraries, images from the web camera is processed and used for face recognition in developing user behavior profiles. The visual module of the robot uses the input from camera to detect, recognize the interactants and analyze facial expressions. When a facial image is detected by the camera, the facial region will be highlighted. This region will then be assigned an ID number. Haar-cascade

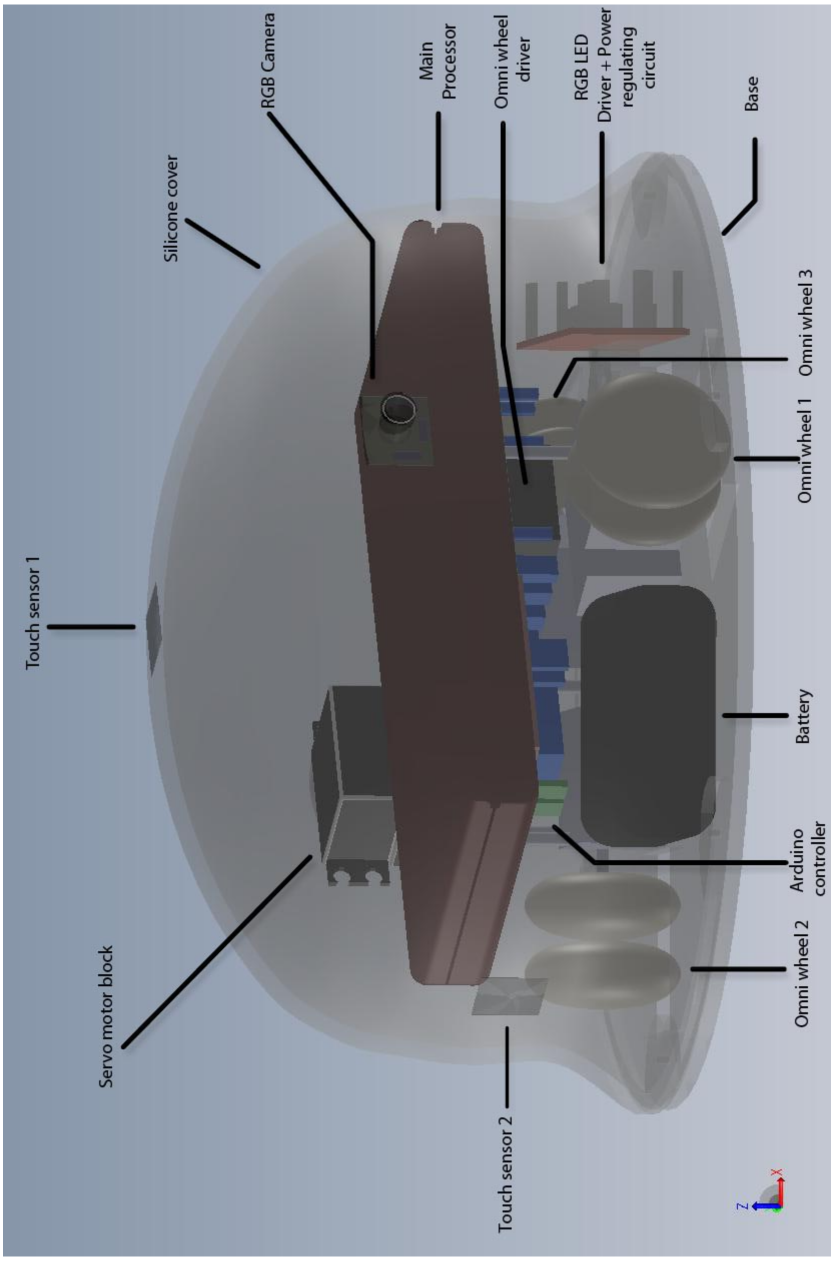

Figure 4.6: Final design of the Lovotics robot.

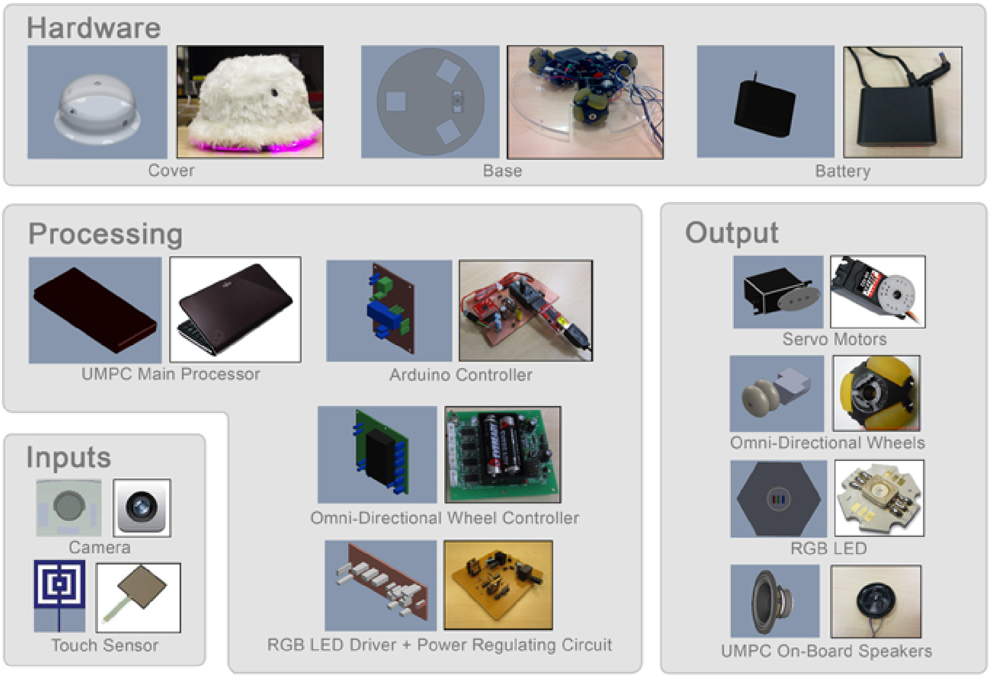

Figure 4.7: Hardware components of the final robot.

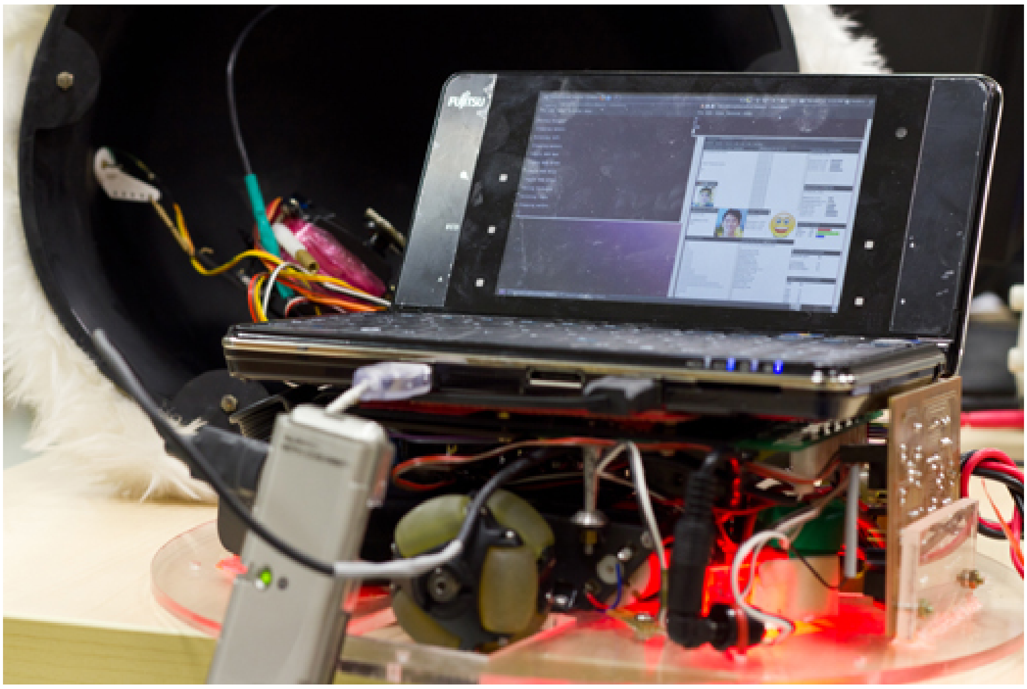

Figure 4.8: Interior of the final Lovotics robot.

Figure 4.9: Final Lovotics robot.

classifiers are incorporated into the Camshift framework to specify the search region in order to achieve both high speed and accurate face detection and tracking.

By comparing the detected face with a stored database of recognizable facial images, the identity of the detected face is computed. After recognition, the detected face will be analyzed to interpret the expression and emotion displayed by the individual. Figure 4.10 shows the visual system in operation.

The database is constructed in a way to support recognition of individuals from the frontal view to quarter-profile view, not exceeding a rotation of more than 45 degrees of the head in the left or right direction. The recognition database contains the facial images of different individuals, with 12 different training images for each individual. Six images are frontal shots of the individuals with minor differences in orientations, while the other six images are quarter-profile shots in the left and right directions.

In addition, to optimize the face recognition process, a dynamic training method has been included to minimize wrong recognition results as best as possible. This method expands the database of the wrongly recognized individual, by including the run-time captured image into the list of training images provided for the person. Maximum limit of 20 training images for each individual is set in the database, inclusive of the basic 12 images mentioned. The average time taken for each recognition process is approximately 1 second. For the first test

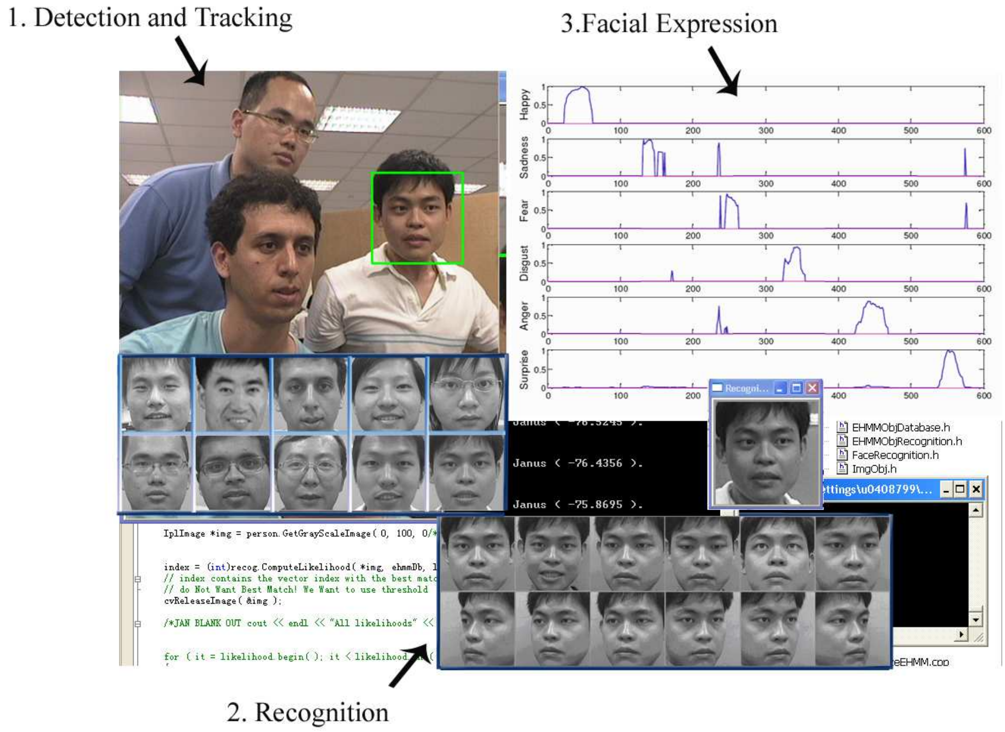

Figure 4.10: The visual input system in operation with the real-time output of three visual processor modules

with the 12 basic training images, the accuracy rate is 94%. With the dynamic learning algorithm, the accuracy rate is increased to 98%.
Continuous output of facial expression for the recognized person is plotted by the system in real-time. This output is transmitted in real-time to the AI module of the robot.

Touch The three pressure sensors lined across the cover of the Lovotics robot are made up of 44.5mm × 44.5mm force sensitive resistors. The sensors are integrated between the fur coat and the silicone skin, and provide touch interaction feedback from the user to the UMPC through the Arduino circuit. Positions of touch sensors are presented in Figure 4.6.

4.2.1.2 Process

The graphical user interface (GUI) of Lovotics software is presented in Figure 4.11. The Lovotics GUI is also accessible via a remote connection while the robot is on operation. Left part of the GUI represents values of input parameters and after being evaluated by each pre-processor module. Data from accelerometer for localization and touch sensors for tactile input is presented first, then the interactant's face is detected and recognized with confidence level and audio input parameters like pitch is demonstrated. Middle part of the GUI represents the PLA and AST values of AI modules. The 13 related parameters of PLA module and probability of love with the detected person is presented. Affective state parameters are also presented in this section. Right part of GUI serves to display the output of the robot, which reflects the current behaviors and emotion of the robot including RGB data of LEDs, omni-wheels movements, and servo motors for deforming the outer cover. Values of hormones in AES module are also presented in this part.

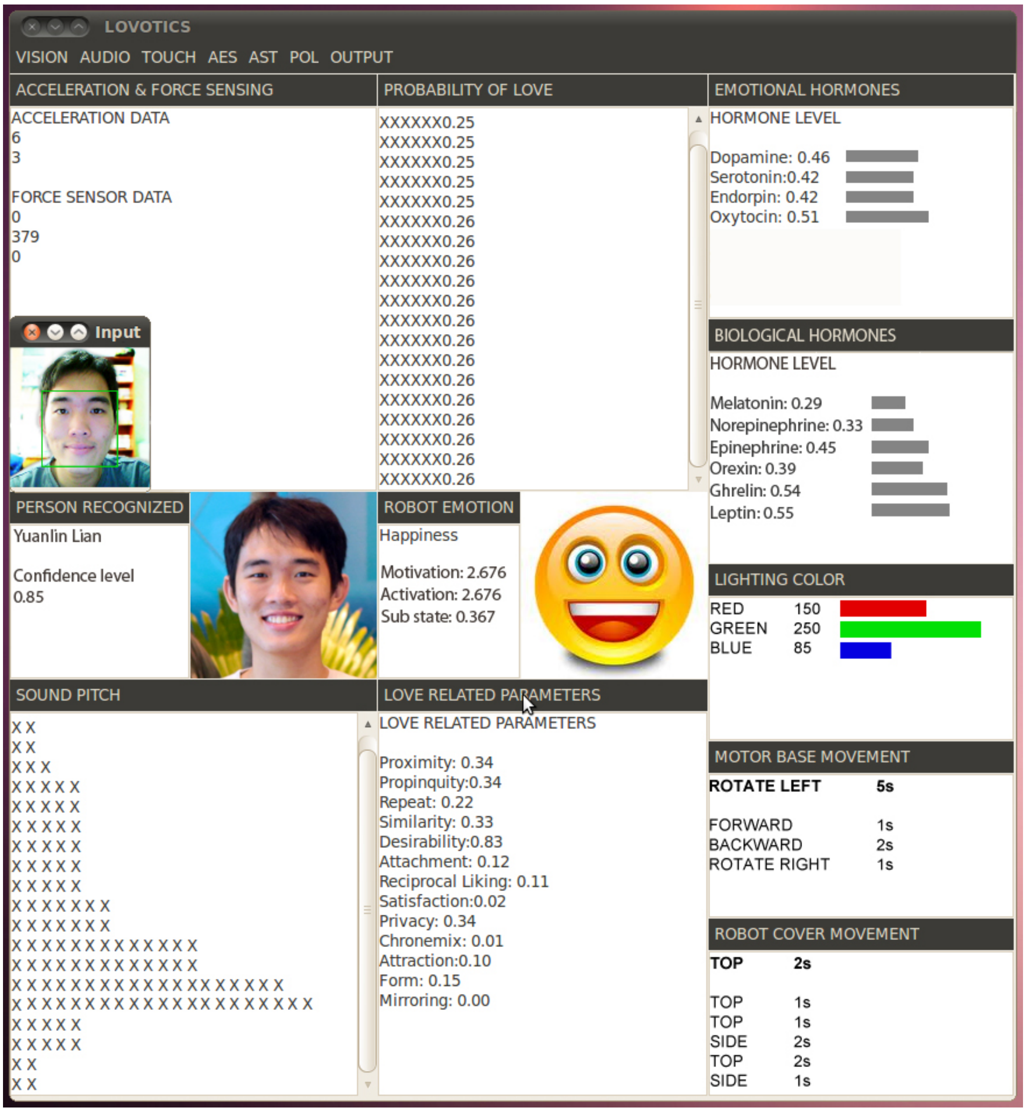

Figure 4.11: Graphical user interface of Lovotics.

4.2.1.3 Behaviors

Results of user study for positivity and likability of Lovotics audio are presented in Figure 4.12.
From Figure 4.12 , it can be seen that trials 1, 3, 13, and 17 (as listed in Table 3.7)

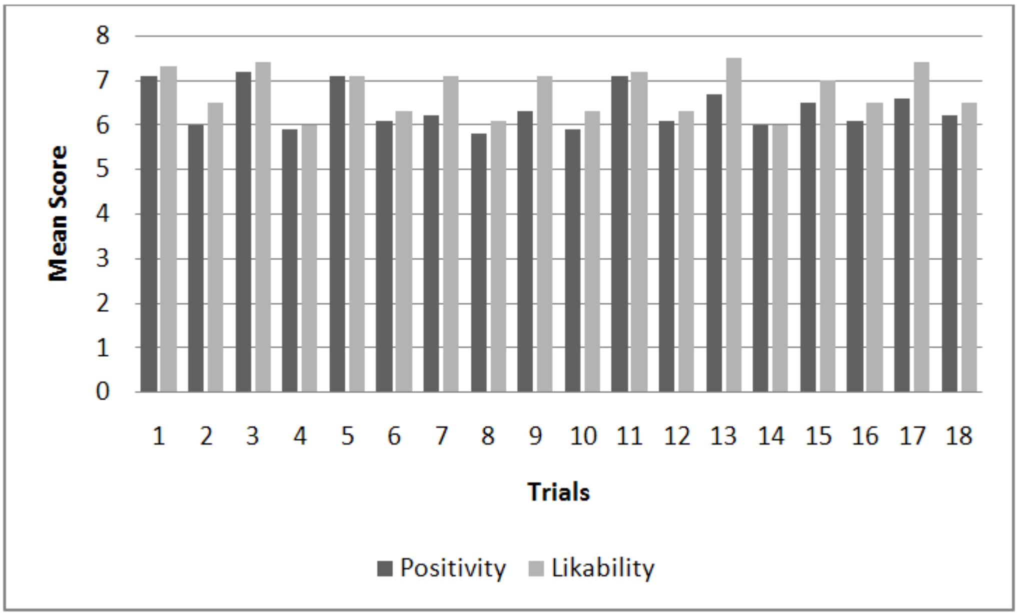

Figure 4.12: Positivity and likability mean scores for 18 different trials. Mean score range is between 0 and 10.

were rated highest on the positivity factor. All 4 tests were consistent in having high synchrony, as well as either 1 second or 5 seconds duration, which shows that sounds exhibiting long or short responses according to the user's input is desirable.
For the likability factor, trials 1, 3, 5, and 11 corresponding to 4 different settings were rated highest. This showed that once again, high synchrony played a major role in determining the level of positive emotions felt after hearing the sounds. Also, nearer distances consistently generated higher levels of positivity as compared to further distances.
Exploratory data analysis were performed before proceeding to the statistical analysis part. It ensured normality of collected data and discarded possible outliers. Another research focus was to examine if there is a relationship between the level of positivity and likability during the whole interaction session and if a relationship was indeed found, also measure the strength of the relationship. We conducted a Pearson correlation coefficient t-test on the two variables (positivity and likability) for examining the relationship between them.
A Pearson correlation coefficient of ($r = 0.838, p < 0.001$) suggests a strong pos-

itive relationship between the two variables, namely positivity and likability. The coefficient of determination, (r^2 = 0.70) denotes the strength of the linear association between the variables.
By engaging the evidence of an association between positivity and likability variables, we evaluated the interaction process tested on the participants. However, the evidence does not support the causality between the variables.
To find and test more structure in our data, let us see further statistical analysis of the three factors.
In the following scenarios [Trial x > Trial y] implies that the mean score of trial x is higher than the mean score of trial y.

- **Study Block A**
  Independent Factor: Chronemics
  Dependent factors: Proximity and Synchrony
  Both positivity and likability display the same trend lines for duration, with preference for either very short sounds or long sounds. However, 5 seconds sounds seem to be the preferred mode, which can be attributed to the fact that people need more time to register a sound and when people are willing to listen for a longer duration, the positive impact is more. Results suggest that short burst of sounds for small duration cannot fully communicate the necessary emotional parameters across to the users before abruptly ending. However small interval sounds communicate well in closer proximities than in larger ones.
  ∗ Trials (1, 2) > Trials (13, 14).
  As far as the dependency of synchronization on chronemics is concerned, the difference between the impact of synchronized and anti-synchronized sounds is lesser for large time duration than for smaller durations, where high degree of synchronization is greatly preferred for a level of intimacy.
  * Difference is minimum in trials (5, 6) and (11, 12) and (15, 16) and (17, 18) while it is maximum in trials (1, 2) and (3, 4).

- **Study Block B**
  Independent Factor: Proximity
  Dependent factors: Chronemics and Synchrony
  For experiments on the distances 0.4 meter, 1 meters, and 2 meters are chosen which represent intimate, personal, and social distances, respectively.
  For proximity, positivity shows no obvious trend, but likability has substantial variation, with 0.4m being the preferred distance. Within this intimate distance, the chances of the interaction session getting positive is highly likely as the participants felt more close to the source of the sound. This induces a feeling of control and hold over the conversation which

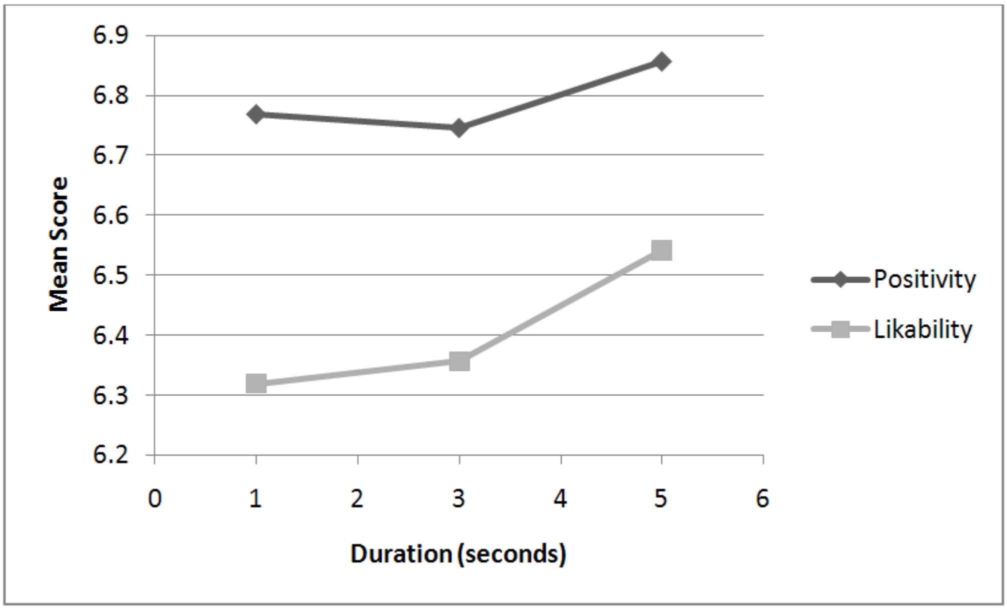

Figure 4.13: Study Block A: Positivity and likability mean scores for chronemics. Mean score range is between 0 and 10.

in turn promotes positive feeling. The participants felt most comfortable interacting at this distance as it lies in an invisible zone of psychological comfort.

Our audio samples were tested highly likable in this interaction.

This tests our research hypothesis that there is a difference in the level of intimacy according to the distance between the human and the robot. People tend to connect more to the robot if it's extremely close to them.

For 1 meter and 2 meters interactions, 3 seconds and 5 seconds duration sounds were preferred as these sounds could keep the user interested for a longer time interval and catch the user's attention. There is a direct linear relationship between proximity and time duration. If the distance is more, the time duration has to be greater to hold the user's interest and promote a liking feeling.

∗ Trial 17, 18 > Trial 13, 14.

For very close distance, there is a high preference of synchronized audio sounds than anti-synchronized ones. Close distance promotes a level of intimacy only if both systems have a high degree of synchronization.

∗ Trial 1 > Trial 2; Trial 3 > Trial 4; Trial 5 > Trial 6.

In fact, even for larger distances, high level of synchronization results in a high chance of a positive feeling but its emphasis is much more in closer proximity.

From our experiments it was observed that participants tend to orient themselves facing exactly to the source of the sound, irrespective of the duration on sound. This strengthens the fact that people tend to feel secure and safe when they can recognize the source of the sound and it is no longer a mystery to them. People would be uncomfortable if the sound came directly from their back.

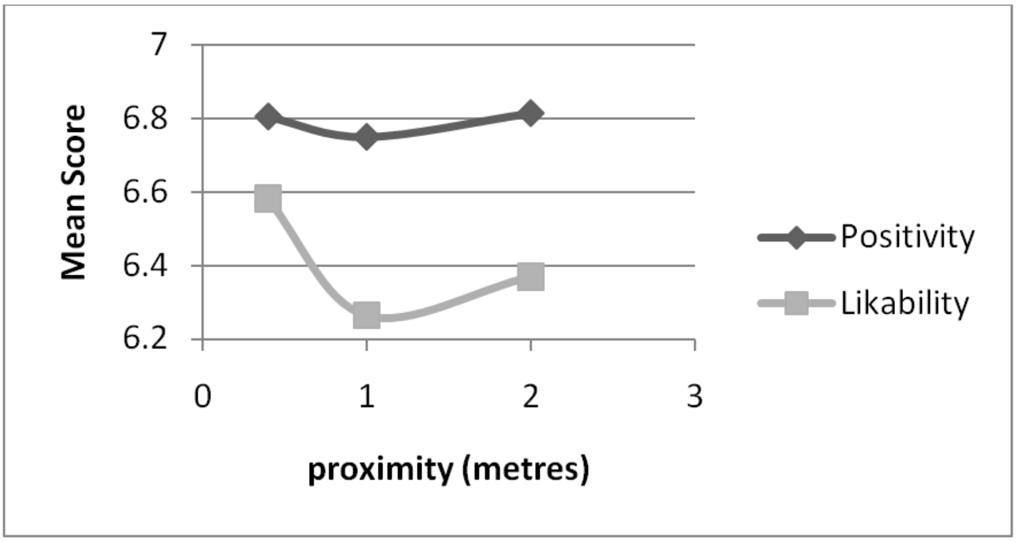

Figure 4.14: Study Block B: Positivity and likability mean scores for proximity. Mean score range is between 0 and 10.

- **Study Block C**
  Independent Factor: Synchrony
  Dependent factors: Chronemics and Proximity
  The results for synchrony show an obvious trend where users prefer synthesized audio with high levels of pitch synchrony as opposed to anti-synchronous sounds. This is consistent with our findings that humans show high level of synchronized behavior when exhibiting attachment or liking, and when reproduced in robots, the effect is still subconsciously preferred. Only for a larger proximity (2 meters) and longer time duration (2 sec), the results showed less difference in between pitch synchronous and anti-synchronous sounds, indicating an attachment is still possible in such trials.
  $*$ Trials 15, 16 and Trials 17, 18.
  The level of synchronization has a linear relationship with the level of intimacy. As intimacy level increases, so does the level of rhythmic harmonic or pitch synchrony. Just as one's body language can convey non-verbal information, pitch synchrony too acts as an effective carrier for non-verbal

messages.
For anti-synchronized sound samples, participants tended to like longer duration of sounds more than shorter ones within personal and social distances. This may be attributed to the fact that participants were willing to listen to understand the sound better. This was a good evidence for testing how effective our designed sound samples were and what impact they made on promoting a connection with the user. This showed that in spite of the anti-synchrony in pitch, our designed sound samples were able to interest the participants and make an impact on promoting a connection with them.

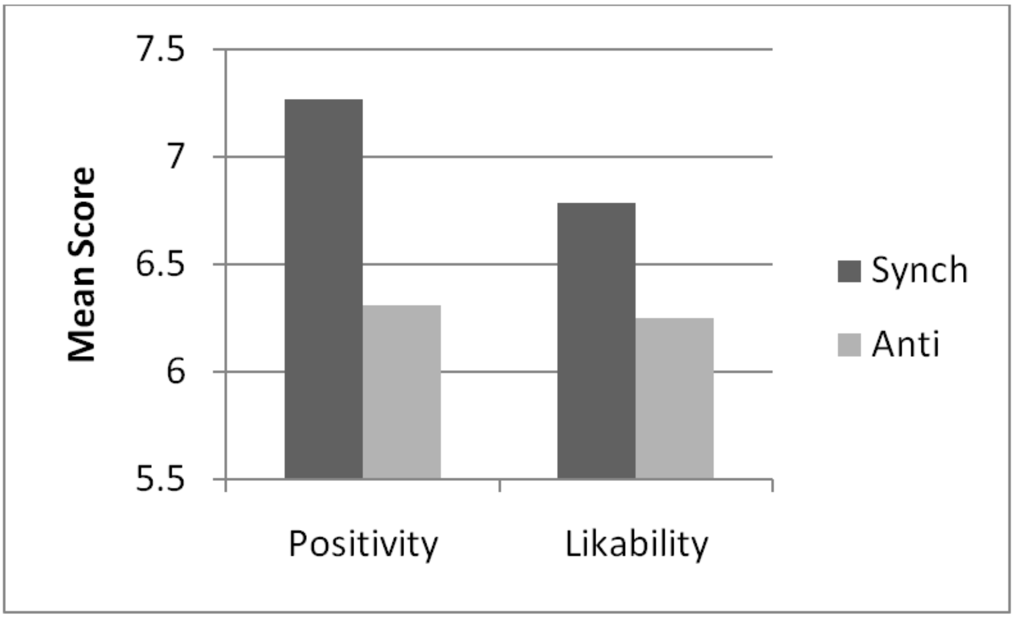

Figure 4.15: Study Block C: Positivity and likability mean scores for synchrony. Mean score range is between 0 and 10.

As explained before, analysis of the user study on chronemics, proximity and synchrony effect on audio shows that a long, synchronized audio sound produced within a closer proximity appeals more positively to the listener as compared to a short, anti-synchronized sound produced from a larger proximity.

4.3 Evaluation

To evaluate the extent and type of love developed in human - robot interaction, ten males and ten females were selected to interact with robot for two hours each. Participants of the user study were academic, research, and administrative members of the Keio-NUS CUTE center which are mostly in the age range of 20

to 35 years old. Participants were familiar with technology and robots in general however selected participants for the user study were not involved in Lovotics project development.
A brief introduction about Lovotics and the idea of human-robot love was presented, followed by a demo to show the features of the robot. The study was conduced for a span of five days and the user interactions were noted. Each user interacted with the robot for two hours at a rate of four human-robot interactions per day, hence completing 20 user interactions in five days. Using the samples of two hours interaction for every user, love scales were calculated and presented in the form of graphs. The open interaction showed various levels of involvement between the robot and the users. After each session, the users were asked to fill a questionnaire, which was designed to evaluate the developed love style. The widely accepted Love Attitude Scale (LAS) was chosen and modified for human-robot love, in the form of Lovotics Love Attitude Scale (LLAS). After completing the questionnaire, the users were asked to review the robot and quote its most attractive and repulsive feature. The gathered information will be used for making further improvements on the robot. The results of study on 20 users (10 males and 10 females) about their interaction with the Lovotics robot are used to analyze the level of bi-directional human - robot love by considering the impact of gender.
Figure 4.16 illustrates few interactions of the participants during the user study.
For human to robot love (*Human→Robot*), the mean values of all six love styles are calculated based on the user responses regarding their feeling about the interaction process; whereas for robot to human love (*Robot→Human*) those values are calculated based on the user responses on Lovotics robot's point of view regarding the interaction process.
These values for human to robot love and robot to human love are calculated separately for both males and females and the results are presented in Figure 4.17 and 4.18 respectively. Mean values of love styles are between 0 and 1. 95% confidence interval is illustrated by error bars.

4.3.1 Human → robot love

From Figure 4.17, it can be seen that the love styles Eros, Ludus, Storge and Pragma have mean values higher than 0.5 (for both males and females) whereas the love styles Mania and Agape have mean values less than 0.5 (for males). This reveals that the users were positively attracted towards robot's appearance, behavior, interaction, and artificial intelligence; but they had less interest in owning the robot and taking care of it. Figure 4.17 also shows that females were more attracted towards the robot compared to males as females have higher mean values of all six love styles for human to robot love than males.

Figure 4.16: Lovotics robot interaction with user during the user study.

4.3.2 Robot → human love

Also according to Figure 4.18, it can be seen that in robot to human love the love styles Eros, Ludus, Storge and Pragma have higher mean values than the love styles Mania and Agape, similar to human to robot love(for both males and females). From Figure 4.18, it is also evident that females found the Lovotics robot was highly attracted towards them than males with respect to all love styles except Agape; whereas men felt more sacrificial and nurture responses by the robot. In coherence with the Figure 4.17, it was found that the robot to human love was more recognizable by females as compared to males.

4.3.3 Human ↔ robot love

To develop a better understanding of the human-robot bi-directional love and the impact of gender, data of Figure 4.17 and Figure 4.18 were merged together to calculate aggregate love. The result is presented in Figure 4.19. Figure 4.19 illustrates that female users felt more love than male users during the interaction process as they have mean values of greater than or equal to 0.5, in scale of 0 to

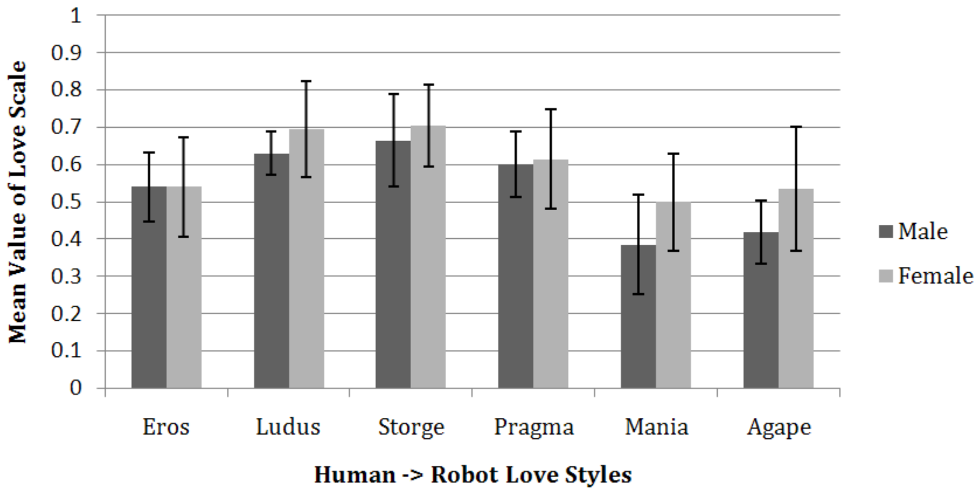

Figure 4.17: Human to robot love, measurement of various love styles from humans towards the robot.

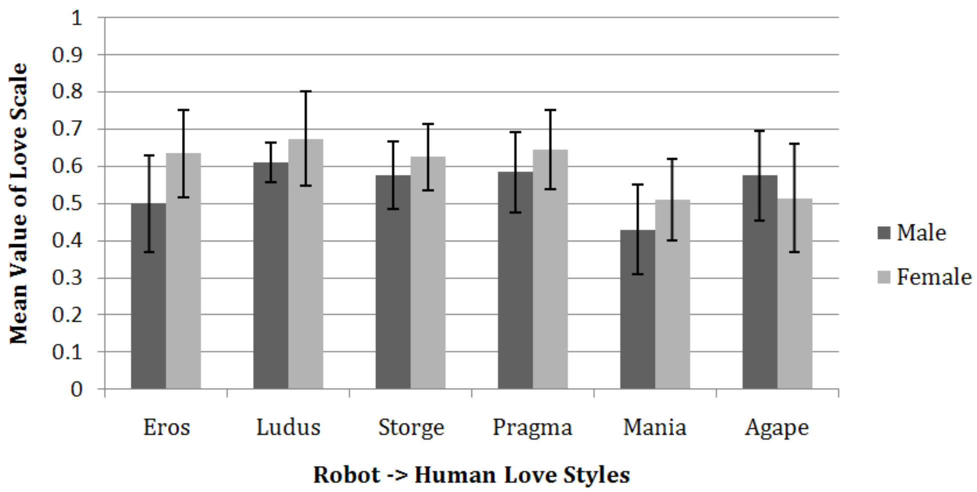

Figure 4.18: Robot-Human Love, measurement of various love styles by the robot, experienced by users.

1, for all love styles. This supported previous observation that females are more interested in the human - robot bi-directional love than males for Lovotics robot.

Mean values of human to robot love, robot to human love, and human-robot bi-directional love are calculated by averaging each parameter's mean values of love styles and all the results are shown on the same graph as Figure 4.20. For both, males and females, it is also found that the mean values of human to robot love, robot to human love and human-robot bi-directional love are almost

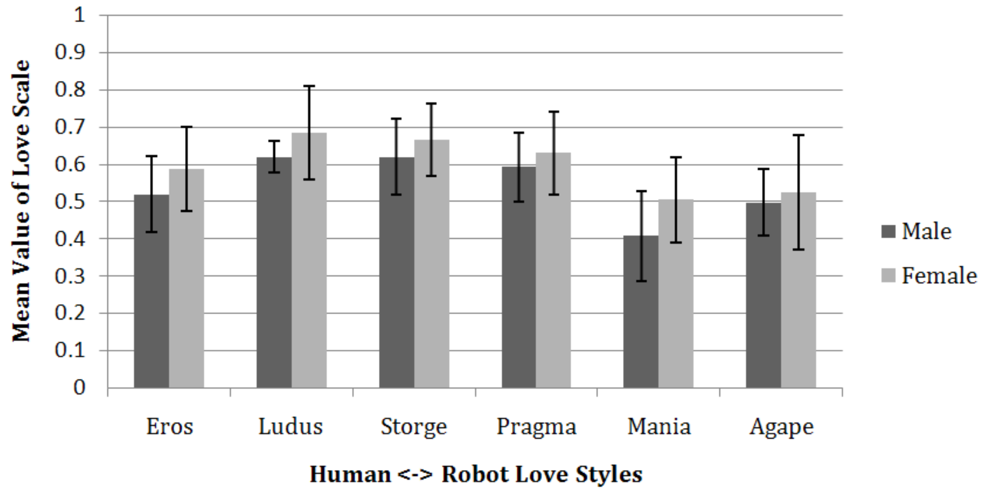

Figure 4.19: Aggregate love, measurement of aggregate love styles developed in Human-Robot interaction.

equal. This shows that the users felt matching love styles and amount of love by the robot, thus establishing a better compatibility and companionship. The two bars of human ↔ robot love in Figure 4.20 illustrate that 8% aggregate love with males and 19% aggregate love with females have been developed.

In order to compare and analyze the impact of each love style in human to robot

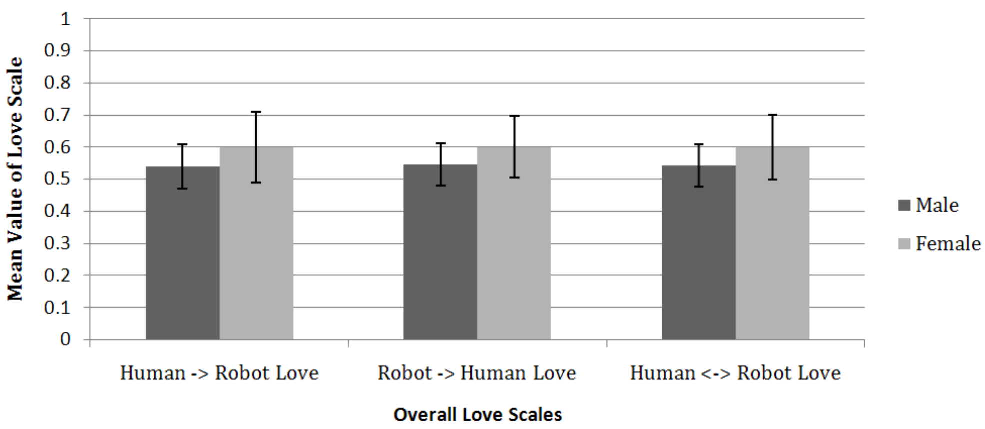

Figure 4.20: Overall love, measurement of overall love developed in human → robot, robot → human, and human ↔ robot interaction.

love and robot to human love, mean values for all love styles are calculated by averaging the rates given by all users for respective styles and the results are presented in Figure 4.21. For the love styles Eros, Ludus, Pragma, and Mania there is no significant difference in their mean values for both human to robot love and robot to human love. The mean value of Storge for human to robot love is higher than that for robot to human love. This reveals that the users are more keen in being friendly with the robot and develop that friendship. Whereas the mean value of Agape for human to robot love is less than that for robot to human love. It was also found that attraction between the users and the robot was mainly due to the appearance, behavior, interaction and intelligence whereas both did not experience high obsession and sacrificial devotion towards each other.

Another research focus was in examining if there is a relationship between the

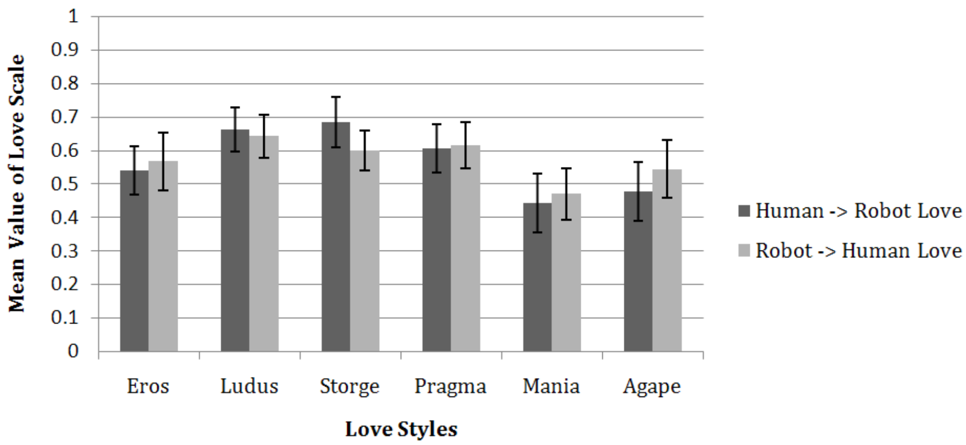

Figure 4.21: Aggregate love, measurement of aggregate love styles developed in Human → Robot and Robot → Human interaction.

level of human to robot love and robot to human love and if a relationship was indeed found, also measure the strength of the relationship. A Pearson correlation coefficient t-tests were conducted on the two variables (level of human to robot love and robot to human love) for all styles of love for examining the relationship between them. The Pearson correlation coefficient values are calculated separately for male, female, and all users, and the results are presented in Figure 4.22.

Overall Pearson correlation coefficient values of ($r = 0.896$; $p < 0.001$ for male users), ($r = 0.904; p < 0.001$ for female users) and ($r = 0.906; p < 0.001$ for overall users), suggest a strong positive relationship between the two variables namely the level of human to robot love and robot to human love. The coefficient of determination, ($r^2 > 0.75$) for all cases denotes the strength of the linear association between the variables independent of gender.

As it is shown in Figure 4.22, for overall users, the love styles Ludus, Storge, Pragma and Mania have higher Pearson correlation coefficient values($r > 0.7; p < 0.001$) whereas the love styles Agape and Eros have slightly less values. For female participants all the love styles except Eros have higher r values. For male participants the love style Ludus has significantly much less r value, represent-

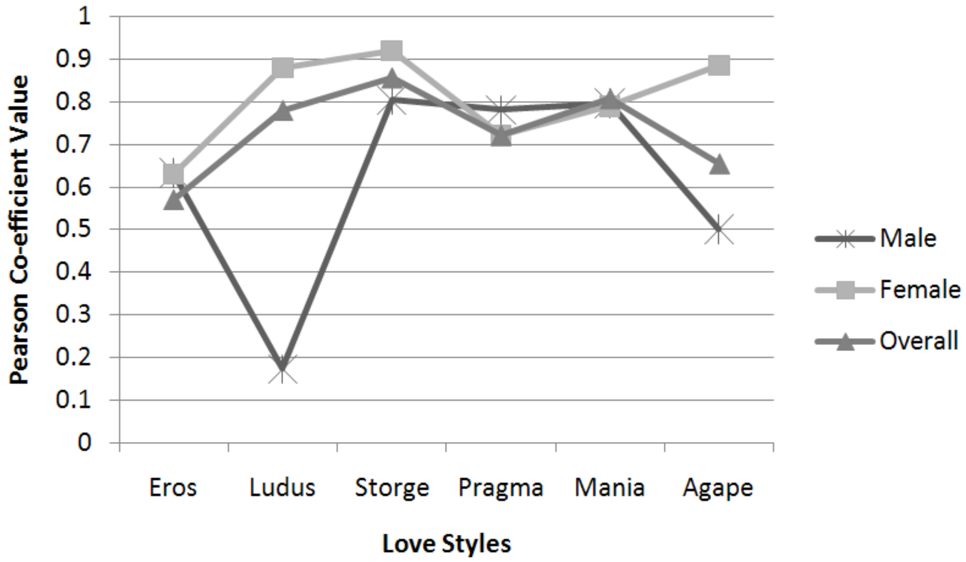

Figure 4.22: Pearson correlation coefficient values of the two variables(level of human to robot love and robot to human love) for all styles of love.

ing a very weak relationship between the two variables regarding this love style.

While analyzing the graphs and gathered data, the following conclusions were drawn:

- Storge love style was the most dominant in terms of love from human towards robot for both sexes.
- The love from robot to human was mostly dominated by the Ludus love style irrespective of gender.
- Ludus love style was most prominent in human robot bi-directional love regardless of whether the person was male or female.
- Storge love style had the highest love scale value in human to robot directional love, and Ludus love scale value was the highest in robot to human directional love.
- Highest mean values for Ludus and Storge love styles indicates two aspects of graduate affection of companionship and enjoyment of playing with the robots.
- Mania love style has minimum values in the evaluation with the values below 0.5 that indicates negative response.

- The female love towards the robot dominated in unidirectional as well as bi-directional love between human and robots. It might refer to the design of the robot which was mostly found cute and adorable by female participants.

Chapter 5

Conclusion

Resembling human love, a sentimental robotics system was presented which consists of a novel artificial intelligence, input analyzer, and behavior generator to develop close relationship between humans and robots. Lovotics introduces a novel interactive robots which focus inculcating intimacy with humans via a slow communication process. Through a long term interaction with robot, interactants build up emotional attachment with the robot. This could create a new form of bi-directional relationship between humans and robots.

Users experience responses based not only on immediate inputs but also on prior interactions and relationships with particular humans. Constant close interaction with the robot can lead to a more intimate relationship. For example, if a new user strokes the robot, it may lead to a lower level of reciprocation when compared to similar action by a person familiar to the robot. Interactions are also influenced by parameters derived from the robots internal state.

Extensive research on scientific aspects of love was performed. Philosophy, biology, and psychology of love were reviewed in litterateurs; several non-verbal behaviors were investigated; and other relevant issues like affective states, hormones, reasons of falling in love, mechanisms of love and state of the art in robotics and artificial intelligence have been researched as the fundamental of Lovotics research.

A design process for Lovotics was presented. In order to invoke human - robot relationships, technological solutions can only take us so far. Design played an important role in order to engage users to explore the possibilities of bi-directional, human-robot love. A user-centric study was conducted in order to understand these factors and incorporate them into Lovotics design. The key issues of design for developing a strong emotional connection between robots and humans were investigated and based on the results of this a robot with minimal design was developed.

Through Lovotics research, an interactive audio interface was developed that is able to enhance positive feelings with the robot when this interface is used in affective communication between robots and humans. Three main parameters of chronemics, proximity, and synchrony were integrated in the robot, in addition to the paralanguage parameters in order to generate desirable sounds which could increase the level of interactive affection between human and robot. The developed audio interface is capable of processing the input human sounds and based on its synthesization, the output robotic sounds are able to communicate with the user in a better way with the enhancement of positive feelings. The user study helped in a great deal in assessing these robotic sounds and modifying them according to the user evaluation and analysis.
An active vision system for face detection, tracking, recognition, and facial expression analysis was also integrated in the robot. Both the Haar-cascade face detector and the Camshift object tracker were integrated to enhance each others' performance for face detection and tracking. The EHMM was used for face recognition and multi-layer perceptrons system was employed for facial expression analysis. Experimental results showed the very robust and accurate performance of the system.
The novel advanced artificial intelligence system of Lovotics was also presented which includes three modules, namely Artificial Endocrine System (AES), which is generally based on physiology of love, Probabilistic Love Assembly (PLA), which is based on psychology of love, and and Affective State Transition (AST), which is based on emotions. These modules were designed and developed inspiring from science of human love and by employment of artificial intelligence methods like Bayesian networks.
A novel method for measuring human - robot love was proposed. This method was employed in order to evaluate the performance of Lovotics robot. Among the two available options of Functional Magnetic Resonance Imaging (fMRI) and User-Study, the latter is adopted and the conventional method of Love Attitude Scale (LAS) is transformed for human - robot interaction as Lovotics Love Attitude Scale (LLAS). A user study was conducted to evaluate the emotional effect of interaction with the robot. Questionnaires were designed based on the psychology of love, especially to measure love scales between humans an the robot. Data from the user study was analyzed statistically to evaluate the overall performance of the designed robot. Various aspects including human to robot love styles, robot to human love styles, overall love values, and gender study were investigated during the data analysis. The user study showed some degrees of bi-directional love between Lovotics robot and humans (8% for males and 19% for females for aggregate love. In general values of love styles was greater with female users which might refer to the cute design of the robot. Further gender study of Lovotics interaction can be conducted in future for additional investi-

gations.
Next step is to conduct an extensive qualitative fieldwork to help gather more data about user responses to the present developed robot and compare with other forms of robots. Using this information, it is possible to further redesign the robot to better evoke the sense of nurture and care within the robot and humans to further their love relationship.
Along with the development of the robot itself, it was tried to understand and define the role of this new genre of robots in the social and cultural context. It is difficult to predict what the relationship will be between humans and robots in the future, and tough questions such as `How does this change our definition of love?´or `Is this kind of love appropriate?´need to be addressed. The way to do this is to continue this study in exploring ``love´´and studying how man and machine are evolving into a new identity and relationship and to create a range of Lovotics robot to tackle these issues.
In future, multiple parallel learning processes handling the learning of different emotional aspects of the robot could be implemented to produce a believable user profile. The parallel processes could be handled in a hierarchal manner where emotions controlling each hardware parameter would have to produce an optimum agenda with subsets of learning processes iterating to meet the requirements.
From user feedback, it would also be ideal to implement voice recognition methods for intimate interaction with the user.
The aim of Lovotics is to pave the way to create personal relationships between humans and robots in the form of Lovotics to exhibit love between human and robotics. Lovotics introduces an interactive method which focuses on inculcating intimacy with humans. This holds potential for creating robots that can interact with humans at a level of emotional sophistication that is still lacking from robots today.

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Appendices

Appendix A

Future Applications

Two possible future applications of Lovotics are proposed as a robotic platform to transfer kiss and employment of robots for leadership.

A.1 Robotic kiss system

In this part, the possibilities for having a realistic, physical and intimate interaction between humans and robots are presented. The emphasize is on the *Kiss Interaction* since the act of kissing is one of the most personnel affections shown by humans to their loved ones. A novel system that provides a high fidelity physical interface for transferring a kiss is proposed, facilitating intimacy between humans and robots not only in the real world, but also in virtual worlds. This concept can be integrated into robotic platforms such as humanoid robots in order to implement humane behaviors like kissing to express affection in a more meaningful and convincing manner.

Kissing is one of the most important modes of human communication that involves physical joining or touching of lips by one individual on another individuals cheek, forehead etc., to convey many deeply felt positive emotions such as respect, greeting, farewell, good luck, romantic affection, and/or sexual desire [75]. Apart from the important communication aspect, kissing also plays an essential biologically motivated role in letting prospective mates to smell and taste each other's pheromones for detecting bio compatibility [252]. When it comes to humans, women are subconsciously attracted more to men whose major histocompatibility complex portion of their genome is different from their own, leading to offsprings with resistance to a greater number of diseases due to heterosis, and thus inheriting a better chance of survival [207].

Roots of kissing dates back as far as to the beginning of the human kind. One theory on the reason of kissing evolved around the practice found in primate mothers, who may have chewed food for their infants and then fed them mouth-to-mouth. Subsequently, pressing the lips even without food may have provided a sense of comfort, closeness, and love. Scientists believe that the fusing of lips evolved because it facilitates mate selection [207, 252].

On the other hand, anthropologists are still to arrive at a consensus as to whether kissing is a learned or an instinctive behavior. In humans, kissing may lead to sexually biased behaviors. It may be due to the grooming behavior also observed among other animals or arising as a result of mothers premasticating food for their children [26]. Non-human primates also exhibit kissing behavior [53]. Dogs, cats, birds, and other animals exhibit licking and grooming behavior among themselves, and also towards humans or other species. This is sometimes interpreted by observers as a type of kissing act.

A comprehensive study of the lip anatomy is required in a physiological perspective in order to gain the natural behavior and manipulation of the lips.

Some of the nerves that affect cerebral function, are involved when we kiss, exchanging messages from the lips, tongue, cheeks, and nose to a brain that conveys information about the temperature, taste, smell, and movements of the process. Some of that information arrives in the somatosensory cortex, a tissue on the surface of the brain that represents tactile information.

The lips loom large because the size of each represented body region is proportional to the density of its nerve endings. Lips use muscular hydrostat mechanism where the volume is preserved, but several deformations are possible due to their muscular structure. The basic kiss depends on a muscle called the orbicularis oris, which is all around the outside of the mouth. When a person kisses the orbicularis oris puckers the lips which also implies that whatever the shape they form into, does not lose any volume. Therefore, essentially when the lip protrudes, the outer skin, rightly so, extends and vice versa takes place when concaves to maintain the volume. This is obvious due to soft watery muscles where no room is for compression.

When a kissing action takes place, there are several hormones and neurotransmitters that are produced in the body and in addition to this process, the body also produces the euphoria most people feel during a good kiss. Psychologist Wendy L. Hill in one of her studies found that one hormone, oxytocin, is involved in social bonding, and another, cortisol, is involved in stress [48] . She also has predicted that kissing boosts up the levels of oxytocin, which plays a major role in social recognition, male and female orgasm, and childbirth. During a kissing process the heart rate increases and the entire body receives more oxygen. During kissing one person feels the smell of the other person and researchers have demonstrated a connection between smells and emotions [233].

Lately, there has been an increasing interest on touch and feeling communication between humans in HRI (Human-Robot Interaction) and HCI (Human-Computer Interaction) communities. Researches around the world have been examining the possibility of embedding haptic to everyday human communication because by nature, humans are physical creatures that long for physical touch [46, 33, 162, 16]. Thus a few attempts to communicate intimacy among humans [242] have been explored. Yet not much attention has been given to the area of social interaction with robotic entities for kiss communication. It is proposed to address this vacuum and give humans and robots a new dimension to express themselves better through kiss communication. Proposed system aims to provide a new high fidelity physical interface for transferring a kiss between humans and robots in real-time or humans and virtual characters through digital media.

In a kissing action, along with its strong emotional and physical connections, a series of physical interactions take place. The slightest of touch of lips exchanges the pressure, softness, and warmth of each lip in a convincing way. This leads to a more biologically apprehensive intimate communication. By observing the human kissing qualitatively and quantitatively, it can be derived that the key physical parameters involved in a human kissing action are pressure/force, temperature and finely controlled lip shape. This whole observation can be linked to the proposed concept of the kissing platform.

The basic idea of this proposed system is to recreate the physical properties incident on one kissing platform by a human lip kiss to another designated kissing platform in real-time with high fidelity. The overall system consist of two digitally connected yet physically isolated kissing platforms. Each one is equipped with life-like lips with high fidelity pressure sensors, temperature sensors, high-resolution linear actuators, and Shape Memory Alloy (SMA) [265] actuators embedded in it. The conceptual model of the proposed system is illustrated in Figure A.1.

The overall architecture of one platform can be modularized as shown in Figure A.2. The main controller module orchestrates the entire system. Mainly it is a embedded system designed to meet the real-time requirements for processing of sensor information and control lip actuation. In the first case, data from the pressure sensors, temperature sensors, and the linear actuator feedback systems need to be periodically read and processed. The data are subjected to different preprocessing in order to account for the inherent stochasticity and imperfections of the sensors. Therefore, high speed digital signal processing takes place in this module to implement various filtering strategies on the data such as dynamic averaging and interpolating. In the lip actuation step, where the kiss recreation occurs, apart from the pure data based control, the system maintains tabulated data of different scenarios of physical kissing, to be referred in intelligent decision making in the kiss recreation step. Processed data is also cross checked with

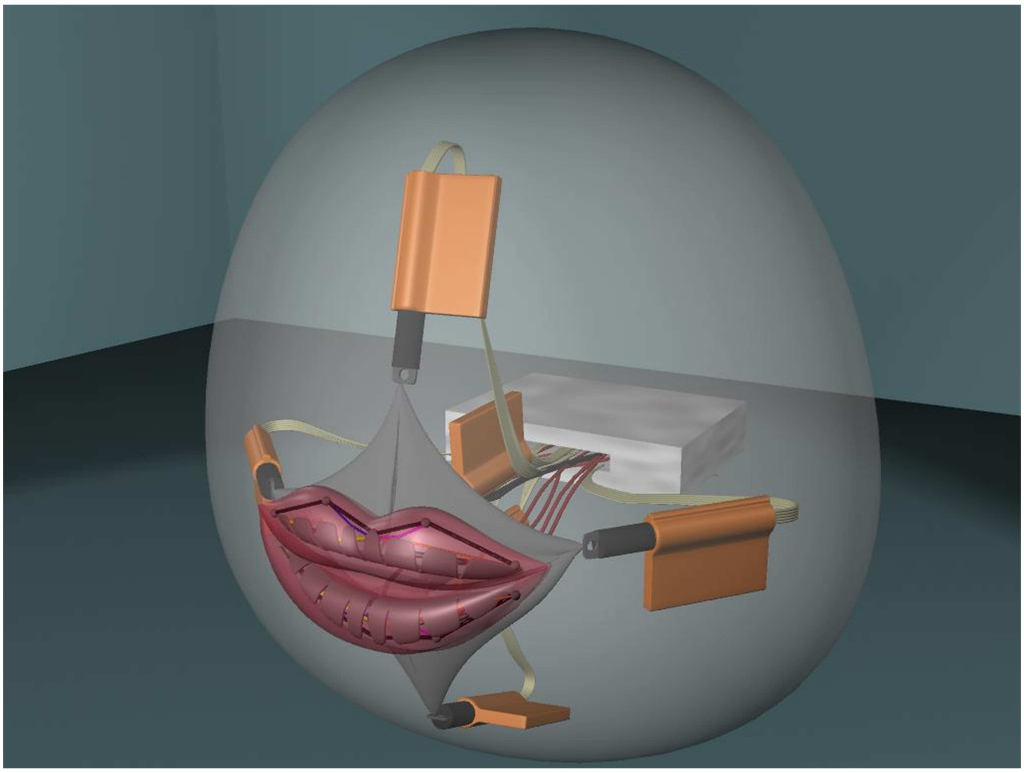

Figure A.1: Proposed kissing platform

that data to adjust and follow the natural lip movement to achieve optimum performance in both qualitatively and quantitatively to match with a real kiss feeling as much as possible.
When a physical kiss interaction takes place on the system, it detects the physical qualities of the kiss quantitatively and encodes it into digital information. All the sensing needs to be done with high resolution and at higher speeds to ensure a successful kiss approximation. The lip is divided into several regions and integrated with each region there is a high resolution pressure sensor capable of measuring minute pressures. All data are exchanged with the coupled robotic systems and this data is utilized to decide the response on the actuation module. Since there are several means to realize the capture of the kiss action, different transformations methods are required. For instance, kiss actuation could employ several classical and novel technologies such as mechanical stimulation, pneumatic stimulation, ultrasound direct nerve stimulation and electrical nerve stimulation. Under mechanical actuation, electrical linear actuators, small pneumatic drives can be considered. In this case, the pressure/force parametric information of the kiss is transformed into mechanical parameters of these actuation techniques (electric power, pressure) accordingly in real-time. Carefully

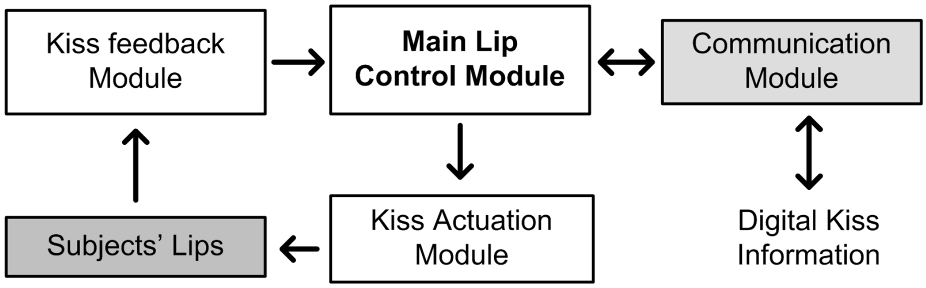

Figure A.2: System overview of the proposed kissing platform

Table A.1: Comparison of Kiss Actuation Techniques

Technology	**Advantages**	**Disadvantages**
Pneumatic Stimulation	Simple Clean	Heavy devices High power consumption
Vibrotactile stimulation	User comfort Low power Noninvasive	Noisy operation Complex implementation
Electrotactile stimulatio	Lower power consumption Light weight No mechanical disturbance	Increased user discomfort

controlled compressed air could be used in direct pneumatic actuation. This can be in the form of air jets or air rings to create the mechanical pressure on the lip surface. Also ultrasound radiated pressure may be utilized in the same manner [123, 122, 124, 90]. Vibrotactile stimulation is another mechanical technique which can be implemented for the kiss actuation by means of voice coils and micro-pin actuators.
In ultrasound direct nerve stimulation, after matching the impedances of the ultrasound source and the human skin, modulated acoustic waves propagate inside the human tissues to excite and activate the relevant mechanoreceptors to elicit tactile feelings. By varying the signal power, modulating frequency, and pulse width different tactile sensations can be invoked [121]. Successful tuning of such a system could be used to electrically transfer the physical kiss properties without mechanical interferences as in mechanical solutions.
Mechanoreceptors in humans can also be excited by electrical stimulation [130]. In this scenario, electric currents in electrodes embedded to the kiss platform excite appropriate cutaneous receptors to provoke tactile feelings. Table A.1 summarizes the pros and cons of the various candidates for tactile stimulation.

Kiss sensing can be divided into two main categories: contact type sensing and non-contact type sensing. In contact type sensing, all mechanical derived pressure/force measuring methods like capacitive, resistive, and piezoelectric could be used. In this case, the transformation may be as simple as the difference in the measured force/pressure. The pressure is only one parameter of the kiss parameters. Therefore, it only gives a very rudimentary approximation of a real kiss. To capture the other qualities like lip shape and temperature we need to consider the other non-contact sensing techniques. High resolution kiss approximation can be done with optical sensing. Its non interfering operation makes a very good candidate in a sensitive application like this. As an added feature, a thermoimaging could also be incorporated to heighten the realism of the interaction. With the advancement of the vision processing field makes its realization straight forward.

The Lip actuation module plays a key role in the system. It could be explained in two levels: macro lip force actuation module and the micro lip shape actuation module. In the macro level, the linear actuator controller module undertakes the precise processing of the pressure applied to the artificial lip. For instance, upon receiving the data from the other device, the control system on the system processes and calculates the actuation of the linear actuators and the SMA wire actuators on board. The actuators work towards neutralizing the sensor data values of the other kiss platform. That is, if the pressure reading on one set of lips is more (somebody kissing it) than the other, it will actuate either to level the pressure or in a predefined limit to recreate the pressure/force value of the disturbance created by the kiss. The algorithmic calculation for the linear actuator displacement is given below. The micro level control of the lip controls the Shape Memory Alloy wires integrated in the lips in the actuation module.

A simple, intuitive control system takes in the measured pressure data of the system and calculates the pressure difference. It is then appropriately scaled down (k_d) and used to determine the necessary positions of each actuator. To achieve the fine pressure control, the system refresh rate has been optimally selected.

$$\begin{aligned} Pkiss_{i,remote}(t_n) - Pkiss_{i,local}(t_n) &= Pkiss_{i,n} \\ Dkiss_{i,local}(t_n) &= Dkiss_{i,local}(t_{n-1}) + Kkiss_{i,D}Pkiss_{i,n} \end{aligned} \tag{A.1}$$

where $i = [1, Mkiss]$ and $Mkiss$ is the number of linear actuators used in the system. $Pkiss_{i,remote}(t_n)$ is the pressure of the i^{th} pressure sensor of the remote kiss platform at time t_n, $Pkiss_{i,n}$ is the pressure difference between the i^{th} pressure sensors of the two systems, $Pkiss_{i,local}(t_n)$ is the pressure of i^{th} pressure sensor of the local kiss platform at time t_n, $Dkiss_{i,local}(t_n)$ is the displacement need to be set at the i^{th} linear actuator at time t_n and $Kkiss_{i,D}$ is the mathematically found constant for the i^{th} linear actuator.

Considering the kissing action, assuming and based on normal kissing actions, for each pressure level, there is a definite lip shape tabulated in the system for different kiss types. This differentiation is done based on the pressure patterns on the lip. For instance, a kiss can be given in any direction on to any part of the lip. Thus the lip shapes in response to these kisses are different. Defining a standard set of lip movements these data are tabulated against the pressure distribution. Upon received a kiss, the main controller checks the most appropriate kind of kiss and chooses the closest data pattern to be applied to the *SMA* actuators. For this task, a pattern matching engine is implemented on the master module. Further, to enhance the human perception, transitions between kiss patterns are allowed to provide the feeling of real-time dynamism.

$$\begin{aligned} Pkiss_{i,remote}(t_n) - Pkiss_{i,local}(t_n) &= Pkiss_{i,n} \\ Pkiss_n &= f\left(Pkiss_{1,n}...Pkiss_{i,n}...Pkiss_{Mkiss,n}\right) \\ SMA_{local}(t_n) &= SMA_{local}\left[Pkiss_n\right] \end{aligned} \tag{A.2}$$

where $Pkiss_n$ is the mathematically calculated value based on the weighted individual pressure differences between the engaged systems and $SMA_{local}(t_n)$ is the Shape Memory Alloy actuators' operating parameters at time t_n.
Since humans maintain almost a constant body temperature, it can safely be assumed that the lips also maintain more or less the same temperature. Therefore, the proposed platforms maintain lip temperature to the average human lip temperature initially. Temperature is measured in the same resolution as of the actuation and communicated to the other kiss system. Temperature adjustments can be done according to the following algorithm.

$$\begin{aligned} Tkiss_{remote}(t_n) - Tkiss_{local}(t_n) &= Tkiss_n \\ Tkiss_{local}(t_n) &= Tkiss_{local}(t_{n-1}) + Kkiss_T Tkiss_n \end{aligned} \tag{A.3}$$

where $Tkiss_{remote}(t_n)$ is the temperature of the remote kissing system at time t_n, $Tkiss_{local}(t_n)$ is the temperature of the local kissing system at time t_n and $Kkiss_T$ is the calculated scaler for temperature adjustments.
The acquired and received data will be manipulated to create and recreate the kissing action physically by the *Main lip control module* of the proposed system. Data is pre-structured to a system specific protocol and exchanged between designated kiss interfaces. Further, the data will be encoded in digital format that enables the communication with artificial entities. *Communication module* ensures the full duplex fast communication between the real and the artificial worlds.
Once we have a this platform implemented, applications can be extended at least to enable three modes of major interactions as follows.

1. **Human to Robot kiss**
   This is the primary mode of operation of this platform. This enables an intimate relationship with a robot or any artificial living being both real and

virtual. For instance, the entity may be in real form like a humanoid robot or a virtual character that senses the world through the digital information fed to the system. In the first case, this platform can be directly attached to the robot where as in the latter case the digitized information may be fed to the virtual character to respond accordingly. Such technology provides a new facility for closer and more realistic interactions between humans and robots.

2. **Human to Virtual character physical/virtual kiss**
   This scenario provides a link between the virtual and real worlds. Here, humans can kiss virtual characters while playing games and receive physical kisses from their favorite virtual characters. This mode is different from the virtual kissing appear in the above section. Here the character is a virtual representation of a real world person, which is an avatar. For example, it can be the virtual personality of a celebrity. A new breed of intimacy involved drama like games, quests, and possibly online activities are also probable once this platform came into being.

3. **Human to Human tele-kiss through the kiss platform**
   It bridges the physical gap between two intimately connected individuals. Since the system has its sensing and actuation modules, without the intelligent response unit it can directly play the mediating role in the kiss interaction by imitating and recreating the lip movement of two human users in real-time using two digitally connected artificial lips. A non real-time kiss communication is also a possibility. These possible extensions are illustrated in figure A.3.

There are a few challenges overcome before a successful intimate interaction is possible with robotic entities. It is not impossible to implement some sort of a kiss transducer on a robotic entity regardless of the physical realization and technology used. The difficult part would be to represent intimacy in machines. For a more closer, emotional interaction, the robots need to have some way of understanding intimacy and affection. It is a relatively untouched area in the field. Artificial Intelligence can come into the picture once a rigorous quantified idea of kissing is established. In order to achieve this, extensive studies need be carried out to generalize the intimacy in machine readable form. There are two forms of intimacy: physical intimacy and emotional intimacy [131]. By the proposed system even though we are aiming at the emotional intimacy, it still requires feelings in various other dimensions for a successful feeling communication [154]. Thus it is evident that a very sophisticated system to capture the every bit of detail is a little beyond the current interests of the

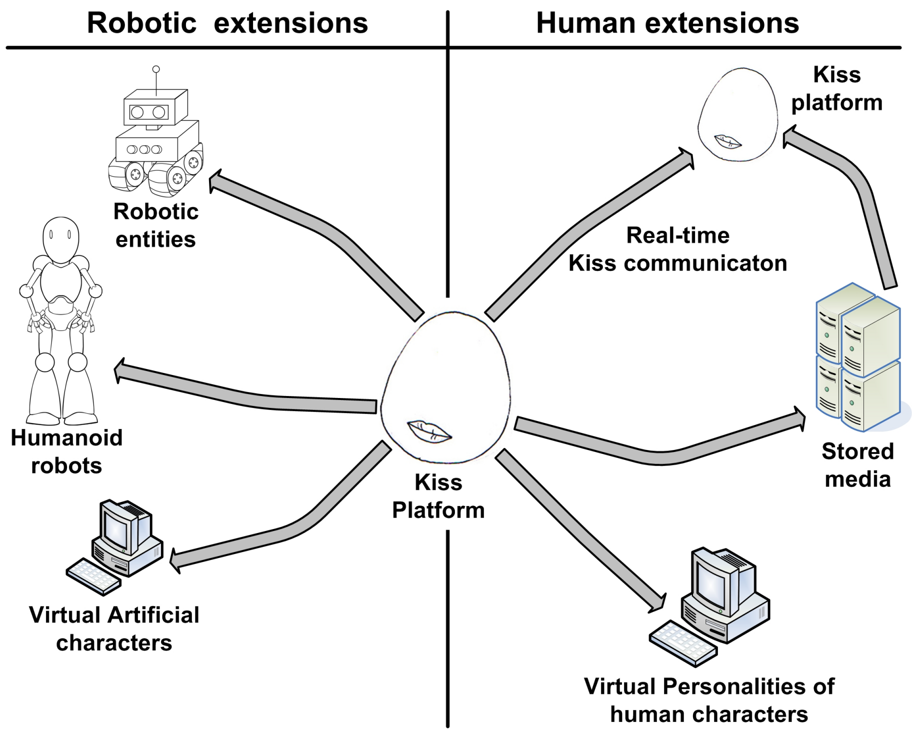

Figure A.3: Illustrated possible extensions of the proposed kissing platform

technology. However, to begin the procedure, it is possible to integrate an artificial intelligence based trained system, to fundamentally identify the kissing action and respond with a kiss.
In mode three, for human to human kiss communication, following topological design considerations should also be addressed:

- Are the devices dedicated to one other device?
- Is communication real-time or stored or both?
- How sensitive should the input mechanism should be?
- How accurate the output mechanism should be?
- What are the other communication media this should bind into?
- How complex the system should be?

In the light of human to human kiss mediation via digitized physical kiss several applications can be achieved:

- One of the main usage of robotic device for kiss is employing that tool for long distance relationships for transferring the intimate feeling. As an example while a mother at work while her kid is at home can be considered for using this technology.

- New technologies require devices to satisfy natural human needs. New devices for better communication could be equipped with more facilities for better communication and proposed technology can be used for Technology adaption.
- Kiss transfer can be added to current communication methods, like voice and webcam for chat, to improve the multimodal communications.

For this scenario, two types of communication for design could be considered, namely real time and stored media. Of course the choice is real-time implementation there is some validity in stored media as well. Tables A.2 and A.3 summarize all the communication means that exist today and highlights various aspects of those in light of kiss communicator.
In the real time method, features of interest consist of high reliability, wide reach and low latency. Bandwidth is not much of an issue since we are not planning to use a high data exchange. According to the table circuit switched data has the highest reach and lowest latency and emerge as the clear choice. But owing to the modern Internet technologies reliability it also can be used. It also has a wider reach and can be used directly without any modification or protocol designing. Table A.2 examines the real-time communication.

In the store and deliver media only thing that matters is reliability. Since all these technologies are mature without any modification we can employ. But in this way, first we record a kiss on the device encode it into data and send it over to the receiving device to be decoded and output. For a starter prototype we can even use a wired communication to simulate the idea. In the later stage use of GPRS is beneficial incorporating Machine to Machine (M2M) interconnectivity. However to get the whole setup using GPRS to work is tricky since most operators do not support static IP allocation to users and peer to peer communication in the first place. Table A.3 summarizes stored media issues.

In this part an idea of a novel platform for human-robot kiss communication is presented in order to move several steps towards carrying out intimate relationships with artificial entities. A general concept of the designed system has been presented in this article. The proposed system will be able to open up new possibilities for human-robot personal relationships by providing facilities for new interactions providing a novel way of transferring a mediated kiss remotely in realtime through interactive media. It allows a high fidelity physical interface enabling kiss communication for several applications, facilitating social communication and intimate human telepresence with both the real and virtual worlds. Proposed platform may positively foster the the man machine co-existence by bridging them in an intimate and physical kiss interaction.

Table A.2: Real-time Kiss Transfer

	Circuit switched data	Over the Internet	Bluetooth® and Zigbee®
Reach	Can be wired or wireless. Reach is very high. For instance, GSM coverage is very strong in many parts of the world.	Last mile can be either wired or wireless. Less reach by developing parts of the world but very much penetrated in developed areas.	Can be used as the first mile of the communication over the Internet. On its own, forms a very small region of coverage within communication is possible at minimum trouble. Unlike Bluetooth, Zigbee has a greater area of coverage up to 60km.
Bandwidth	Up to 14.4 kbps. Sufficient for this project.	Varies	Up to 1Mbps
Latency	Very low - Uses dedicated lines. Therefore minimum delay when using reliable protocols	Low - Varies with the protocol used. If reliability to be ensured need to compromise some speed.	Very low
Reliability	High	Varies with the protocol	High
Availability	High	Varies with the location	Very small coverage area (private coverage area)

Table A.3: Transferring the Kiss through Stored Media

	SMS	MMS	Database
Reach	Greater coverage	Greater coverage	Limited coverage
Size (data)	Very limited - In typical single message only 160 bytes and in concatenated messages up to 500 bytes.	Up to few kilobytes worth of data.	Greatest size. Even up to Mega byte scale.
Reliability	Very reliable	Reliable	Reliable Depend on the protocol being used
Availability	High	Acceptable	Low (pico networks)

A.2 From robot relationship to robot leadership

The role of robots can be changed from *labor* to *leader*. In this section few key issues for robot-based leadership is explained. Specifically emotion-laden leadership by robots, robot leadership advantages, and modes of robot leadership are highlighted.

The role of emotion in leadership is extended to robotic applications and possibility of improving robot-based leadership by focusing on emotional attachment is presented. Emotion-laden leadership by robots addresses the core of leadership and that is emotions and feelings among leader and followers. These emotions are the backbone of the influence exerted by leader on followers. Therefore, introduction, exploration and development of Lovotics is important for robot-based leadership to be effective.

Various reasons which support the idea of using robots for leadership are explored. These key issues are embodiment, multitasking ability, anthropomorphism, programmability, programmability, deduction, reasoning and problem solving, decision making and planning, learning, imitation, collaboration, adaptability, modularity, believability, repeatability, interactivity and Connectivity.

Several modes of robot leadership are explained. Role of humans and robots in robot-based leadership is explored. Admin, crew and factor based configurations are investigated and both centralized and decentralized methods are presented.

Recent technological achievements like computers, internet and mobile phones play an important role in management nowadays. Such facilities can be embodied in the form of robots to be employed for robot-based leadership. Robots can be a new generation of computers with physical existence to handle various management and leadership tasks.

There are several advantages for robots over computers which bestow them the capability for better leadership. The main advantages of robots for leadership is explained. Another key issue is that robots are capable of developing emotional attachments with humans. Such ability is another focused of this paper.

Several application are practically imaginable for the next generation of robots. For example robot-based leadership could be useful for health care sector to achieve consistently high precision. Not only robots can be employed as a servant or assistance but also they can lead an operation in health care. As an example a surgery can be performed by a robot while different human surgeons cooperating with the robot for each specific task during the surgery. Robots are capable or multitasking and such ability can be employed to allow the robot to interact with different humans in real time. Such robot-based leadership application in surgery is one of the many examples of using robots for leadership.

Leadership can be described as a specifically emotion-laden process, with emotions entwined with the social influence process [93]. The leader's mood in an

organization effects the group in three levels: The mood of individual group members, the affective tone of the group and group processes like coordination, effort expenditure, and task strategy [228]. The capability of understanding and managing moods and emotions in the self and others which is known as emotional intelligence contributes to effective leadership in organizations [92].
Considering the importance of emotion in leadership, it should be also applied in robot leadership. Generally emotional attachment can improve the relationship between humans and robots. Robots can be in an active participant in the human-robot interaction and build up emotional attachments with humans.
Also robots are capable of detecting emotional states of the humans during interaction mainly through visual and audio interactive channels. Hence bi-directional emotional attachment between humans and robots is achievable. Emotional intelligence of the robots can be employed in improving the emotional values of the leadership aspects.
There are several reasons that robots can be engaged for leadership. Some of them are very similar to capabilities of computers and some are advantages of robots over computers. In general, robots can be known as new version of computers with physical presentation. Several advantages of robots are listed here to support the idea of employing robots for leadership:

- **Embodiment:** Robots can act as concrete manifestation of computers as have the capability to interact with the environment through a physical body within the surroundings. Embodiment is a key advantage of a robotic leader compare to a computer.

- **Multitasking ability:** One of the key challenges in leadership is dealing with various tasks in the same times. Simultaneous operation of several actions by a robot is feasible and this ability is one of the key advantages of a robotic leader compare to a human.

- **Anthropomorphism:** Anthropomorphism is the attribution of human characteristics to animals or non-living things, phenomena, material states and objects or abstract concepts. Since robots have physical embodiment, anthropomorphism can be applied to them and proper design of the robot would increase this parameter for better acceptance in leadership. Anthropomorphism can be applied to robots as well which needs to be considered in the design of the robot with specific role of leadership.

- **Programmability:** Programmability is one of the basic capabilities of the robots. Such capability can be adapted from computers to certain applications and requirements for robots.

- **Deduction, reasoning, and problem solving:** Human beings solve most of their problems using fast, intuitive judgments rather than the conscious, step-by-step deduction that early AI research was able to model [250]. Robots can employ artificial intelligence to deal with uncertain or incomplete information, employing concepts from probability and economics [175]. There are several attempts in artificial intelligence research to imitate this kind of sub-symbolic problem solving. By employing several artificial intelligence tools robots can be equipped to perform different tasks which require deduction, reasoning, and problem solving.

- **Decision making and planning:** Robots are capable of planning using artificial intelligence by visualizing the future by having a representation of the state of the world and being able to make predictions about how their actions will change it. For planning robots should be able to make choices that maximize the utility and value of the available choices [199]. Planning skill of the robots can be employed for their leadership to plan future requirements logically.
- **Learning:** Machine learning has been central to artificial intelligence research from the beginning [237]. Supervised, unsupervised, and reinforcement are three main methods of machine learning [190]. Learning capability of robot makes it possible to learn several methods of management to improve their leadership skill.
- **Imitation:** In addition to two common methods of teaching robots, which are explicitly telling them via programming and letting the robot to figuring out itself via common leaning algorithms, imitation is another method to let robot learn via observing human behaviors [17]. Robots can imitate leaders behaviors to perform some leadership tasks.
- **Collaboration:** Robots are capable of collaborating with humans and also with other robots. Robots may cooperate for multi-agent planning to achieve a given goal. Emergent behavior such as this is used by evolutionary algorithms and swarm intelligence [199]. Robots may collaborate together and also with humans to perform different tasks of leadership. As a leadership a team of robots and human leaders can work together to use advantages of each group to optimize the performance in a management tasks.
- **Adaptability:** Robots can be built according to the certain usage and their form and functionality can be customized according to a specific environment. Furthermore robots can be employed in some environments for management and leadership where the it is impossible or difficult for humans to attend.
- **Modularity:** Beyond conventional actuation, sensing and control typically found in fixed-morphology robots, self-reconfiguring robots are also able

to deliberately change their own shape by rearranging the connectivity of their parts, in order to adapt to new circumstances, perform new tasks, or recover from damage. As a common type modular reconfigurable robots-experimental systems made by interconnecting multiple, simple, similar units-can perform shape shifting [263].
Leader robots may be designed in a modular configuration to perform accordingly base on the requirements.

- **Believability:** Plausibility is one of another advantages of robots compare to computers and mobiles phone. Base of the usage robots can be designed with believable behaviors and expressions. In this way robots will be more acceptable by humans.

- **Repeatability:** Robots are capable of repeating as task many times and such quality can be used for repeatable leadership tasks.

- **Interactivity:** Interaction is one of the essential elements of many leadership task and robots are capable of that. Researchers from different disciplines are trying to improve human - robot interaction modalities.

- **Connectivity:** Robots can be easily connected to a network and employ that network facilities. The robot can be connected to the internet and exploit world wide web instantaneously and use GPS data for localization.

Collaboration between robots in a leadership team can be performed in various formations according to the temperament of the environment and system requirements. These leadership modes can be surveyed from several outlooks.
A robot-based management system can be consist of robots and humans. As a members of the team, each human or robot may have different degree of influence on the team performance. It might be controlled merely by a human or only a robot or both of them. Role of humans and robots can be different in each application. Following categories can be considered for this mode based on the role of each human and robot:

- **Robot as a leader:** A robot can be the main leader of the robot-based leadership system. In this case, the robot leads the entire system and acts beyond the leadership members.

- **Robot as a support for leadership:** Current human-based leadership teams use tools and technologies like computers and internet to expedite their leadership. Robots can be next generation of such facilitators. In this case robot supports the leadership task as a tool.

- **Robots as intermediate leaders:** In an specific case for the previous category, robots can act as mediator between humans to facilitate a leadership task. Many of current successful technologies are those which act between humans as a link to connect them together with offering novel practical application. Internet-based social networks are good example of recent useful technologies which are employed by humans for better performance. In the same way, robotic systems can be intergraded within a leadership team to open new gates in leadership methodologies.

Leadership tasks can be performed via a team of robots or even team of robots and humans together. In this case robots collaborate together in order to perform a task and humans may be also engaged in such action. Hence tasks should be allocated to members in appropriate way for optimum performance. Several configurations of the robotic can be be arranged for such performance. Admin, Crew and Factor based are three common methods of task allocation in robots [204]. These modes can be extended to robot leadership. Considering a team of robots and humans as members of an organization following three methods can be applied to leadership:

- **Admin-based:** In a reliable and robust situation that the central robot can manage other members of the team including robots and humans admin-based method can be applied for team configuration. In this case one robot plays the role of administrator for team performance and manages other team members.

- **Crew-based:** In crew-based configuration, the main leader is not involved directly due to the structure of the system or requirements of platform but different members of the organization may communicate safely, then the team members including humans and robots may communicate to decide for different modules of leadership.

- **Factor-based:** Factor-based configuration applies to a team of robots and humans when each of the members can handle each task individually. One of the possible application of this case is in lack of reliable communication between one member with not only the central leader, but also between the members.

An organization can be equipped with a centralized leadership system consist of humans and robots. In such system the central management unit manages all the organization. On the other hand, such team can be managed via a decentralized robot-based leadership system.

Appendix B

Ethical Issues

Lovotics attempts to bridge the gap between humans and robots and opens doors to new paradigms of research. As humans are involved in interaction via Lovotics, the influences and consequences that it may bring into society should be given special consideration, especially now that the ethical aspects of robotics have gained sufficient importance to be debated in international forums [11, 194] In this era of advanced technology, we not only need to create machines that help accomplish various tasks but also cultivate and exceed humans in moral values, focusing on preserving culture, history, art, and science. It is evident that robotic entities are being adapted widely and deeply into our lifestyles and are much more prevalent than people may realize. Furthermore, it is apparent that a technological revolution is beginning to take place in every aspect of human life. This will certainly affect our culture and society but it is not yet evident whether it is for better or for worse. The following are some of the aspects of ethical issues that might give birth as a result of this.

- **Singularity:** As machines are becoming more advance and more human-like, in the future these entities may reach or even exceed human intellect to an unimaginable extent by today's standards. This will bridge the gap that currently exists between humans and machines. This issue has been referred to as Technological Singularity [244]. The future generation will not only use these entities for accomplishing various tasks but also learn to care, love and show affection towards them.

- **Rights of robots:** David Levy argues that despite the fact that robots cannot feel pain and suffering like animals, they should however be endowed with rights and should be treated ethically. This conclusion is based partly on the reasonable expectation that many of the ways in which we will treat artificially conscious robots will be similar to the ways that we humans treat each other, and therefore ethical behavior towards such robots is merely an extension of such a treatment [146]. In the same way those ethical issues should be further extended to argue the rights of a robot in a human - robot relationship.

- **Robot's will:** The recreation of human - robot digital love may create a major concern on society. Some people may argue towards the free will of the robot [260]. The main goal of Lovotics is to develop a robotic system which is liked by humans and also gives the impression of offering the same likeness back. Hence Lovotics is a human centered research, focusing mainly on satisfaction of humans without much consideration of the robot's desires. One may argue that love desire of the robot should be considered as well.

- **Limited sense of ethical and societal values of robots:** As humans are involved in this emotional interaction, the influence and the ethical issues that it can raise should be given special consideration. Unlike humans, robotic entities have a limited sense of ethical and societal values. Obviously ethical issues should be considered by designers and programmers of robots not only during the design process but also during the application of robots.

- **Exploiting natural limits to satisfy needs:** Humans may exploit natural limits to satisfy physiological and psychological needs. They may miss-use the Lovotics platform and with no defined limits this may lead to abuse.

- **Psychological problems due to lack of human contact:** Since this platform can be used to transfer special affection to another human being, prolonged attachment to the robot may give rise to psychological problems due to the lack of human contact [194].

- **Negative influence due to the lack of physical affection:** As this robotic platform could also be used as a long distance emotion transfer device, people who are geographically dispersed may tend to express their feelings to each other through the Lovotics interface. This may create a negative influence on both parties since they may not experience the actual physical affection.

- **Social exclusion:** According to research findings social exclusion could result as well. This can be elaborated through an experiment done on young monkeys where they were left in the care of robots and as a result were unable to move with their fellow monkeys and were unable to breed [119].

- **Positive affection towards distant parents and children:** This platform could be seen as a basis for positive affection towards the society. As a robot could be used to transfer emotions to loved ones, especially between parents and children, it will bring physical comfort and satisfaction, which is a vital need for young children when their parents are far apart.

- **Care and concern towards the elderly:** Further more considering the elderly, this will be more than just a platform to transfer emotions but also bring moral satisfaction, caring and concern.. Although this platform bridges the relationship act between humans and robots, opening doors to new paradigms of research, the consequences that it may bring into the society should be given special consideration.

- **Create an illusion of life:** In spite of the fact that this system can be used to express love and devotion towards another person, it can have a negative impact on society, especially by creating a illusion of life where humans may fail to express true physical affection towards another human. People however, may find it as an *easy mechanism* to care for another person, for instance in the act of caring for elders.

Appendix C

Publications

- H. A. Samani, A. D. Cheok, M. J. Tharakan et al. (2011) ***A Design Process for Lovotics***. In Springer, Human - Robot Personal Relationships, Springer LNICST series , Volume 59, 118-125, Presented in 3rd International conference on Human-robot personal relationship - HRPR 2010.

- H. A. Samani, A. D. Cheok (2011) ***From Human-Robot Relationship to Robot-Based Leadership***. In 2011 IEEE International Conference on Human System Interaction - HSI 2011.

- H. A. Samani, A. D. Cheok, N. Fernando (2011) ***An Affective Interactive Audio Interface for Lovotics***. In ACM Computers in Entertainment, Vol. 9, No. 2, Article 6, July 2011. Presented in International Conference on Advances in Computer Entertainment Technology - ACE 2010.

- H. A. Samani, A. D. Cheok (2010) ***Probability of Love between Robots and Humans***. In 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems - IROS 2010.

- H. A. Samani, A. D. Cheok, A. Nagpal et al. (2010) ***Towards a Formulation of Love in Human-Robot Interaction***. In 19th IEEE International Symposium in Robot and Human Interactive Communication - RoMan 2010.

- S. Nomura, K. S. Teh, H. A. Samani et al. (2009) ***Feasibility of Social Interfaces based on Tactile Senses for Caring Communication***. In The 8th International Workshop on Social Intelligence Design - SID 2009.

- H. A. Samani, D. Polydorou, T. Marsh, A. D. Cheok (2009) ***Emotional Intelligence Engine for Serious Game***. In 40th annual conference of International Simulation and Gaming Association, Learn to Game, Game to Learn - ISAGA 2009.

- A. D. Cheok, I. S. Godage, H. A. Samani et al. (2009) I***ntimate Physical Interaction with Robots , Human Robot Kiss***. In 2nd International conference on Human-robot personal relationship - HRPR 2009.
- H. A. Samani, A. D. Cheok, I. S. Godage (2008) ***LOVOTICS : Adding Love to Human-Robot Relationships***. In ACE International Conference on Advances in Computer Entertainment Technology - ACE 2008.
- S. S. Ge, H. A. Samani, Y.H.J. Ong, C. C. Hang (2008) ***Active Affective Facial Analysis for Human-Robot Interaction***. In The 17th IEEE International Symposium on Robot and Human Interactive Communication - RO-MAN 2008.
- H. A. Samani, S. S. Ge, C. C. Hang (2008) ***LOVOTIC : LOVE and ROBOTIC Affective States Based on Visual Perceptions***. In 1st International conference on Human-robot personal relationship - HRPR 2008.

Updated list of publications and videos of the robot are available on Lovotics website: http://www.lovotics.com

In the summer of 2011, Lovotics research was discovered and promoted through media around the world. Lovotics has been featured in media such as Reuters, CBS News, Spiegel, Washington Post, Los Angeles Times and more (List is available online in http://news.lovotics.com).

List of Symbols and Abbreviations

Abbreviation/Symbol	Description
AES	Artificial Endrocrine System
AI	Artificial intelligence
ANG	Anger
AU	Action unit
AST	Affective State Transition
DBN	Dynamic Bayesian Network
DIS	Disgust
EDA	Exploratory Data Analysis
EHMM	Embaded Hidden Markov Model
FEA	Fear
fMRI	Functional Magnetic Resonance Imaging
GUI	Graphical User Interface
HAP	Happy
HCI	Human - Computer Interaction
HRI	Human - Robot Interaction
LAS	Love Attitude Scale
LLAS	Lovotics Love Attitude Scale
MFCC	Mel Frequency Cepstral Coefficients
MLP	Multi Layer Perceptron
NLP	Natural Language Processing
SAD	Sad
PLA	Probabilistic Love Assembly
SMA	Shape Memory Alloy
SUP	surprise
Human → Robot	Human to robot
Robot → Human	Robot to human
Human ↔ Robot	Between human and robot
$f_{(.)}$	Vector-valued nonlinear function
$h_{(.)}$	Vector-valued nonlinear function

Abbreviation/Symbol	Description
a	First image data
b	Second image data
c	Constant coeficient
d	Distance
e	Variable
f	Function
h	Sampling time
i	Variable
j	Variable
k	Constant coeficient
l	Variable
m	Variable
p	Pearson's population correlation coefficient
r	Sample Pearson correlation coefficient
t	Time
u	Radius
v	Number of variables
w	Weight
x	Random variable
y	Random variable
z	Counter
A	Transitional probabilities between super states
B	Observation density function of embedded state
C	The area of the environment
F	Vector
K	Stiffness function
N	Number of super states
M	Mass center
O	Observation vector
P	Probability
Q	State sequence
S	Super state
T	Total time
U	Covariance matrix
X	First axis in Cartesian coordinate system
Y	Second axis in Cartesian coordinate system
Z	Third axis in Cartesian coordinate system
$A1$	Number of weak classifiers
Act	Activation
Amp	Amplitude
Ara	Area of the robot's surface
Aud	Audio Matrix
Cl	Class
$Dkiss$	Kiss displecament
E_k	MLP output

Abbreviation/Symbol	Description
En	Envelope
fe	Feature
H_n	Number of harmonics
hei	Height
l_i	Length
$KKiss$	Kiss constant
Mot	Motivation
Pch	Pitch
pr	Parity
Sub	Sub-state
Tem	Tempo
$TKiss$	Kiss temperature
tr	Threshold
wid	Width
x_c	First mean value of location
y_c	Second value of mean location
z_k	Scaled output
$\Re$	Real numbers
α	Non-linearity factor
β	Affective state coefficient
ε	Error
η	Adjusting parameter
θ	Degree
λ	Set
μ	Gaussian parameter
π	3.14
τ	Intermediate veritable
ω	Classifier
Γ	Learning rate
Δ	Differecnce
Λ	Parameter set
Π	Initial probability
$\vec{r}$	Point
$\vec{S}$	Affective state vector
$\vec{\Delta}$	Affective state transition verctor
$\vec{\Phi}$	Gravitational field vector