Practical Considerations for the Design of Autonomous Mobile Robots

Conor McGinn and Kevin Kelly

Department of Mechanical and Manufacturing Engineering,
Trinity College Dublin, Dublin 2, Ireland

ABSTRACT

This paper addresses the practical challenges that engineers encounter when designing autonomous mobile robots. The issues faced are multi-disciplinary in nature and become exponentially more complex as the behavioural diversity and robustness requirements of the robot are increased. In response to the need for a highly effective generalised suite of principles to aid the design of autonomous machines, a set of eight practical design guidelines are proposed. These principles directly complement the embodied design principles which represent one of the most complete design methodologies developed to date. The effectiveness of these principles is qualitatively assessed through direct comparison of a robot platform designed using these principles with an analogous platform which was not.

KEYWORDS: robotics, design,

1. Introduction

The process of designing of autonomous mobile robots that can function in dynamic environments is challenging and extremely complex. The difficulties faced can be attributed to the multi-disciplinary nature of the task and the number of practical constraints that are imposed on mobile robots that operate in real-world environments. In the field of mobile robotics there is no 'one-size-fits-all' morphology and few widely accepted industrial standards exist.

The diversity of the behaviour that the robot can exhibit is directly proportional to the complexity of the subsystems that the robot possesses and the manner in which they are interconnected. Therefore as robots become more sophisticated, their design becomes increasingly complex. To add further complication to the design process, the designer is also faced with many physical design constraints. Environmental uncertainty, adherence to physical laws and limitations in power, sensing, computing, materials and actuation technology serve to further complicate and make difficult the process of developing 'intelligent' robot machines. Considering the many challenges that engineers face in developing autonomous robots, it is surprising that few generalised design methodologies exist that guide the integrated design of mobile robots at a systems level. As a consequence, perhaps, few practical multi-functional robotic platforms are in existence. Instead researchers tend to focus on the development of robotic subsystems or on the development of mobile robots that are capable of a small number of specialised tasks.

To succeed in developing autonomous mobile robots that are capable of reliably undertaking a diverse range of tasks in unstructured environments, the robotics research community must acknowledge the importance of systematic design methodologies. There is an urgent need for a widely accepted design framework that can guide researchers and engineers through each stage of the design process – from conception to assessment. In section 2, traditional and contemporary approaches to robot design will be presented. Particular focus will be given to embodied design as it seems to be the most complete methodology developed to date. Despite its promising potential, there are some key practical issues associated with the embodied design philosophy. These problems will be directly addressed in section 3 through the development of a formalised set of practical design principles. In section 4, the effectiveness of these design principles will be assessed through the qualitative comparison of two social robot interfaces. In section 5 conclusions will be drawn.

2. Autonomous Mobile Robot Design Methodologies

In the early days of artificial intelligence and robotics research it was widely believed by researchers that computers could be capable of displaying 'intelligence' through manipulation of symbols alone. This idea became known as the symbol-system hypothesis (SSH). Central to the SSH is the idea that intelligence can be realised internally, independent of a body. In accordance with the SSH, early autonomous robots realised 'intelligence' through manipulation of internal models of the robot's local environment. The robot's model of the environment was continuously updated through sensor measurements and motor control was based upon interpretation of this model. This design methodology relies fundamentally on the ability to accurately model the rules and laws of environmental interaction. While this method worked relatively effectively with certain robots that acted within deterministic environments, it fared terribly when tested in stochastic real world scenarios. Not only did it turn out that the real world was far too complex and unpredictable to model in a computer simulation but the computational effort required to make even the most basic of decisions was excessive.

In the mid 1980s, Rodney Brooks at MIT proposed a novel design philosophy known as the 'subsumptive architecture' [1] and showed that very simple robots could exhibit complex behaviours through adoption of this method. This methodology promotes the idea that specific behaviour should emerge directly from interaction with the environment (no internal models required).

2.3 Embodied Design

Through successful demonstration of the subsumption architecture, Brooks and others demonstrated that intelligent behaviour was emergent from a robots interaction with the environment. This established what has become the first widely accepted principle in the design of autonomous mobile robots – an autonomous robot that possesses 'intelligence' must be able to actively interact with the environment. In other words, autonomous robots must be embodied agents.

The first formal development of embodied AI principles can be traced to two papers written by Brooks in the early 1990s. In these papers Brooks criticises the feasibility and methods that engineers had used up until that time and proposes a bottom-up design methodology for the realisation of intelligent embodied robots [2-3]. This methodology consisted of four design principles (1) situatedness – robot should be situated in the environment and not deal exclusively with abstract descriptions (2) embodiment – the robot should have a body and possess the ability to affect the environment through interaction (3) intelligence – the robot should be observed to be intelligent (the source of this intelligence can be attributed to either the computational engine or the emergent interaction between the robot and the environment) (4) emergence – the intelligence of the robot emerges from the robots interactions with the environment.

As the embodied design methodology gained in popularity over time, the original design principles were expanded and refined. In a groundbreaking book published in 2006, authors Rolf Pfeifer and Josh Bongard argue the principles of embodied intelligence form a coherent basis for a general theory of intelligence [4]. In their book, Pfeifer and Bongard present the theory of embodied intelligence through a series of generalised design principles that span three time scales – the here-and-now perspective, the ontogenetic perspective and the phylogenetic perspective. Due to the completeness and relevance that these design principles have to the design and development of autonomous robotic agents, these principles are currently the closest thing that robot engineers have to a standardised methodology through which mobile robots can be developed.

The intended function of the design principles presented by Pfeifer and Bongard is to form a general theory of how intelligence is manifested in embodied agents. Although the design principles provide an excellent insight into the nature of intelligence and how it might be realised on a machine, they provide little direct instruction for how these principles might be practically implemented on robots. Therefore there is a direct need for a generalised design methodology that incorporates both the embodied design principles and guidelines associated with the practical issues associated with the realisation of intelligent robotic agents.

Traditionally researchers turn to functional or bio-inspired design principles to guide the low-level design of autonomous robots. It is noted that although functional and bio-inspired design methods can be applied to guide the implementation of embodied principles, both design methods exist independently of the embodied design methodology and are often used by robot designers in isolation.

2.4 Functional Design

Robots developed in adherence to the functional design philosophy are designed with functionality and practical performance at the forefront. This design method shares many similarities with traditional top-down industrial design approaches [5] where the design process is typically iterative and appraisals are made based mostly on quantitative practical performance.

Functional robots are designed to exhibit a high degree of 'productness'. Robots designed in this manner are typically associated with terms such as 'reliability', 'safety' and 'efficiency'. Examples of functionally designed robots include industrial robot manipulators, robotic vacuum cleaners, and robot lawnmowers.

In accordance with the formalised set of functional design principles for the design of autonomous robots developed by Yavuz [6], the problem robot design can be broken down into three primary areas (1) mobility (2) navigation (3) autonomy. Through detailed engineering analysis of these three areas, a functional designer can optimise the electro-mechanical design of a robot such that the robot will possess increased efficiency. It has been shown that application of functional design principles can significantly improve the overall practical performance of autonomous mobile robots [6].

It can be argued that the majority of problems associated with functional designed robots can be linked to the top-down methodology that underlies the functional design process. As the robot is typically designed for a specific purpose, the number of tasks the robot can undertake is limited and the effectiveness of the solution is generally heavily dependent on the operating environment [7]. The top-down ideology dictates that the primary focus should be on developing robots that merely appear intelligent with little emphasis on the internal processes that produce this behaviour. This typically reduces the robustness of the design and further constrains the robot's operational boundaries. Robots designed in accordance with functional design principles place minimal emphasis on inherently qualitative factors such the richness of interaction between the robot and human user. Functionally designed robots provide especially weak social models and are unlikely to elicit an emotional response from a person.

2.3 Bio-Inspired Design

Biologically inspired robots are designed through the analysis and reverse engineering of systems found in nature. The bio-inspired methodology is motivated by three key factors (1) systems found in nature have been optimised through evolution to be highly efficient (2) people are more likely to be able to relate to and accept machines that possesses life-like attributes (3) to serve as physical models that we can use to help understand natural systems. Typical examples of bio-inspired robots include robotic pets, robotic fish and snake-like robots.

Functionality plays a secondary role in the design of bio-inspired robots. While functional robot designers can divide the problem of mobile robot design into three sub-categories, bio-inspired designers are likely to make many more categorisations. Bio-inspired designers are concerned with additional issues including the robot's capability for social interaction, anthropomorphism and aesthetic similarity to natural forms.

While robots developed in adherence to the bio-inspired principles appear to be far more suitable for general purpose use due to the deeper cognitive, locomotive and social models they possess, this not always the case. An implicit assumption that is made in the design of bio-inspired robots is that robots should be built in a fashion similar to humans and other 'intelligent' animals. There are two fundamental problems associated with this assertion. The first problem is associated with the theoretical issues associated with the design of bio-inspired machines. As we have yet to unlock many of the most fundamental secrets behind how people and animals operate, it seems unlikely that we can (with current knowledge) construct systems capable of possessing analogous forms of 'intelligence'. The second fundamental problem is a technological one. Despite technological advances over the past few decades, sensors, actuators and computing technology continue to substantially lag their animal analogues. For example, even if we have a good working understanding of a biological process such as human gait, it may prove practically impossible to replicate on a robot. Another practical limitation of this design methodology arises from the additional design constraints that bio-inspired designers enforce on their robots. Generally speaking sensors and mechanisms not naturally found in nature are not employed on biologically inspired mobile robots. For example, bio-inspired robots tend not utilise infinite rotational mechanisms (wheels/tracks) for locomotion. This significantly reduces the means through which environmental sensing can be achieved, interpretation can be made and action can be taken.

3. Practical Principles of Robot Design

It is apparent that the optimal design for a modern day autonomous, general-purpose mobile robot should adhere to embodied design requirements and possess a range of functional and bio-inspired practical features. The eight design principles presented in this section have been developed through detailed assessment of the literature and are intended to address some of the most fundamental (and often underappreciated) issues associated with the physical realisation of autonomous mobile robots.

1) Aesthetics Principle

This principle states that robots should be aesthetically pleasing and non-threatening to the human user. It is observed from the literature that that physical appearance has been shown to bias social interaction. For example it has been demonstrated that good looking people are perceived as more intelligent [8] and that stereotypes are closely connected with physical appearance [9]. Therefore in order to ensure that a robot will be accepted by users, it is crucial to pay attention to the robot's aesthetic qualities. As people have a tendency to anthropomorphise robots, there is an ethical responsibility on the designer to ensure that expectations created from the aesthetics of the design should provide a reasonable account of the robot's abilities (functional and social).

2) Containment Principle

The containment principle implies that the robot’s internal mechanisms should be contained inside a fixed volume where possible. As research has shown that people’s perception of the robot's reliability is negatively affected by the visible presence of external hardware [10], efforts should be made to internalise as much of the robots hardware as possible. This containment has an added bonus of serving to shield sensitive parts from the environmental hazards such as water, dirt and dust.

3) Customisation Principle

According to the customisation principle, robots whose form and behaviour can be modified to suit the tastes and preferences of the individual human user will have a better chance of being accepted by people than those that are not. Also as customisation serves to increase the number of ways in which the robot can comply with the environment, the diversity of tasks that the robot can undertake will increase.

4) Discriminative communication of system states

It is evident from several studies involving field tests with mobile robots that a defined focal point on the robot that provides continuous feedback to the human user is highly desirable (robots that lack the ability to reliably communicate tend to confuse and frustrate the user)[10-12]. The discriminative communication of system states principle operates on the premises that the nature of the information contained within what is being communicated should have an importance weight associated with it and that this importance weight should bias how the message is transmitted to the human user. For example, the explicit communication to the user that the robot's battery is about to die will have a higher importance weight than a basic social greeting or communicating the current time/date.

5) Mechanical Complexity Principle

The mechanical complexity principle states that the diversity of behaviour that a robot possesses should be attained by as simple a mechanism as possible. To illustrate the importance of minimising mechanical complexity, consider the design of a mobile robot that has 10,000 moving parts in comparison to an equivalent robot that utilises only 100 moving parts. Although the performance of both robots may be identical in theory, as the former robot possesses significantly more moving parts not only will servicing the robot be more challenging, expensive and time consuming but it will have many more possible failure modes.

6) Mechanical robustness

The robustness principle states that robots should be mechanically sturdy and capable of surviving reasonable knocks and bumps without serious damage. As the real world is dynamic and unpredictable in nature, it is likely that the robot will subject to occasional knocks and falls. In both natural and synthetic life, resilience is a key requirement for survival and the more robust a robot is, the longer it will last and the more successful it is likely to be.

7) Software Complexity Principle

The software complexity principle is the software analogue of the mechanical complexity principle which dictates that mechanical complexity should be minimised as long as the minimisation doesn't affect adversely affect the robot's performance. The software complexity principle states that the computer architecture employed on a robot should enable the robot to be easily programmed. Programs should be highly modular in form (such that they can be tested and analysed independently of the robot) and addition of new modules should not require significant modification of other modules and source code in the system. The benefits associated with modular implementation in this manner have been previously identified by Brooks [1].

8) Design for evolution

The 'design for evolution' principle simply states that robot designs should try to maintain generality such that they can be easily upgraded and evolved over time into a more advanced and capable design. By identifying and directly addressing observed performance issues in the current design, future generations of the robot can be developed to better address present limitations and are thus likely to be more robust and capable of exhibiting increasingly diverse behaviour. In order to ensure the successful evolution of the robot in this manner, it is important that robots are not overly dependent on specific components such that successive redesigns become overly dependent on these features.

4. Case Study

In order to validate the practical design principles outlined in section 3, it is necessary to show that robots developed through direct utilisation of these principles are inherently better suited for practical application than those that are not. As the motivation for the design of mobile robots typically varies from robot to robot, it is generally difficult to make direct comparisons between robots on a global scale. However as social robot interfaces can serve as independent robot platforms and since the role of social interfaces doesn't tend to vary much between designs, the practical performance of two social robot interfaces can be better compared. In this section a direct comparison will be made between two social robot interfaces. While both interfaces adhere to the embodied design methodology to a similar degree, the robot developed with consideration given to the design principles presented in section 3 is substantially better suited for practical operation.

The first robot to be considered is the robot 'Kismet'. Kismet was developed in the 1990s by Cynthia Breazeal at MIT and was arguably the first robot capable of maintaining convincing social interaction with human users in real-time. Kismet provides a suitable benchmark to compare against as it remains among the most referenced social interfaces in the scientific literature and the somewhat iconic status Kismet has gained in the popular media. Furthermore the physical characteristics of Kismet are representative of many of the most common robot interfaces that have been developed to date. Like the majority of social robot interfaces, Kismet consists of a mechanically actuated head with independently controlled facial features including eyes, eyebrows, ears and mouth. Kismet has 21 degrees of freedom overall (6 devoted to controlling eye gaze and head orientation and 15 controlling facial expression) [13].

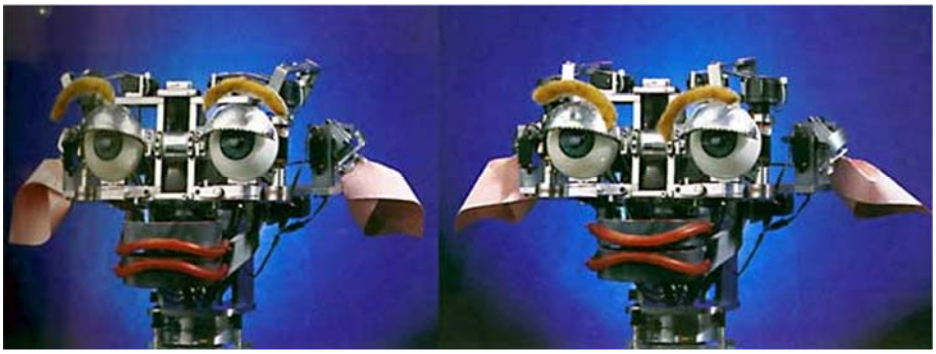

Figure 1: The robot Kismet manipulating its facial expression to show emotion

Illustration 1: http://sweb.cityu.edu.hk/sm2240/1/robot.htm

While Kismet is capable of displaying a diverse range of believable expressions and can engage in natural turn-taking behaviour with human users, it can be observed that the physical design of Kismet's interface is inherently limited in several ways. It is acknowledged that as Kismet was developed primarily to provide a believable means through which intelligent social interaction could be demonstrated, mechanical design played a lesser role in the design criteria of the robot. Therefore the contribution of this section and indeed this paper is not to criticise the design of Kismet and robots like it but to suggest ways in which their design might be modified such that it may be used more efficiently over longer periods of time and across a wider range of environments.

The robot that Kismet will be compared to is 'Mac', a robotic interface currently being developed at Trinity College Dublin. Unlike Kismet, this interface has been developed through close consideration of the practical design principles identified in this paper. Like Kismet this interface consists of an actuated head that possesses a face with active facial features. However these facial features are not realised mechanically but graphically through a small LCD screen mounted in the front of the head. In addition, Mac possesses a matrix of LEDs arranged in a manner similar to a human's hairline. The colour of these LEDs can be independently controlled by the onboard microcontroller embedded in Mac's head.

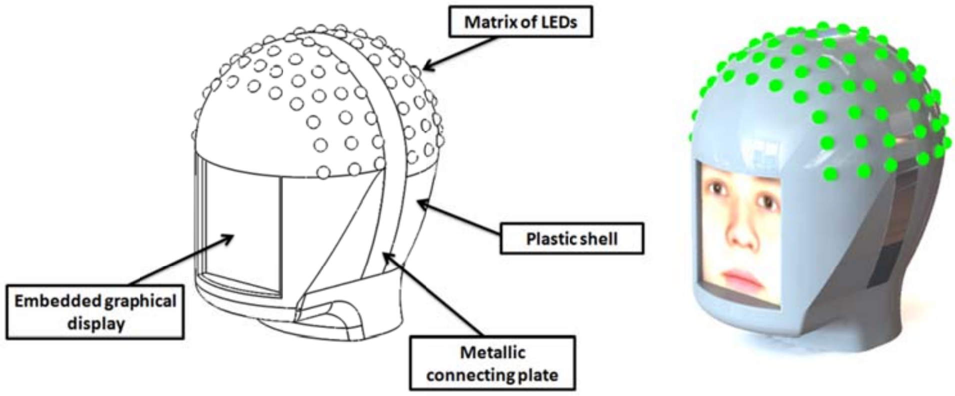

Figure 2: Overview of the Mac interface

From an aesthetics perspective both heads are very similar. Both Kismet and Mac have heads that are approximately humanoid in shape and possess facial features analogous to those in humans. Whilst both robots possess human-like features neither robot aspires to directly replicate humanlike appearance. The biggest aesthetic difference between the robots is that Kismets features are mechanical in form and actuation while Mac's are graphical.

Mac has been designed such that operational hardware has been internalised inside the facial structure. Not only does this serve to increase the user's perception of the robots reliability but it also protects many of the systems components from exposure to the environment. In the case of Kismet, little conscious effort has been made to hide and protect internal mechanisms.

Robots that utilise mechanised facial features are inherently more difficult to customise than those that utilise graphical displays. In order to modify the appearance of Kismet, replacement parts are need to be manufactured and installed. Furthermore the mechanical design of the interface constrains the form that these replacement parts may take. In general most mechanically actuated faces of the same type appear approximately identical. It is noted some mechanical interfaces such as those developed by David Hanson that utilise artificial skins can possess visually distinct faces without changing the underlying mechanisms [14].

Social interaction is only a subset of the field of Human-Robot interaction and therefore robots that operate in the vicinity of humans should possess the means for interacting with people on several different levels. While Kismet is capable of engaging in relatively rich social interaction with human users through its facial displays, it performs poorly in its ability to differentiate what it is communicating (all communication it does through manipulation of facial expressions and voice) and in the visibility in which users can receive the communication (humans need to be within line of sight of Kismet's face). One of the biggest strengths of Mac's design is its ability to communicate with human users. Like Kismet, Mac can engage in social interaction with human users through manipulation of its facial features and head orientation. However by codifying the LEDs on Mac's head, it is possible to continuously communicate information that is poorly suited to expression via manipulation of facial features (i.e. battery state, current operational mode). This method of communication not only facilitates the discriminative emission of information but provides a means of communication that can observed over a significantly larger temporal range than those expressed through facial representations alone (humans need to be within line of sight of Kismet's head). In addition, the graphical display on Mac's face can be manipulated to provide direct feedback of sensory states (i.e. display stream from onboard vision system).

The difference in mechanical simplicity between Kismet and Mac are obvious. While Kismet possesses 21 degrees of freedom and requires significant mechanical complexity to realise this motion, Mac possesses effectively infinite degrees of freedom (degree of freedom depends on the complexity of the graphical face model) with only the actuation requirement to manipulate the orientation of the head.

Kismet with its protruding features, exposed hardware and mechanical complexity is significantly more likely to suffer serious mechanical damage than the Mac robot that has no protruding features, no exposed hardware and a physically robust housing structure.

Admittedly the software to control Mac's facial expressions and to enable sensory information to be visible through the graphical display is noticeably more complex than that of Kismets (although the underlying perception-motor processes between both robots are similar).

Kismet is a good example of a robot that is poorly designed for evolution. Increasing the degrees of freedom the robot possess, redesign or reorientation of facial features and enabling high levels of customisation are examples of how future generations of Kismet may be improved. It is difficult to foresee how Kismets design can be improved in this way over successive generations without major structural changes being made. On the other hand Mac has been designed such that iterative improvements can be made over time. Increasing the complexity of the facial features, enhancing the LED interface and increasing the diversity of facial features that can be represented by the robot are all examples of how the robots performance can improve over the phylogenetic time perspective.

5. Conclusion

Despite rapid progress over the past few decades in the field of robotics, few widely accepted generalised methodologies exist to guide and assist in the design and practical construction of autonomous mobile robots. Although the embodied design philosophy appears to provide many insightful considerations needed to realise practical artificial intelligence, few (if any) methodologies directly address the practical issues associated with developing robots to be used by civilians over long periods of time in dynamic, real-world environments. In this paper eight practical design considerations were presented that directly address this practical considerations related to robot design. Through qualitative comparison between a social robotic interface developed in adherence to these principles and one that was not, it was shown that the former robot is inherently better suited for robust operation in real world environments.

6. References

[1] R. Brooks, “A robust layered control system for a mobile robot”, IEEE Journal of Robotics and Automation, 1985.

[2] R. Brooks, “Intelligence without representation”, Artificial Intelligence, vol. 47, no. 1–3, pp.139-159, 1991.

[3] R. Brooks, “Intelligence without reason”, Artificial Intelligence: critical concepts, no. 1293, 1991.

[4] R. Pfeifer and J. Bongard, “How the Body Shapes the Way We Think: A New View of Intelligence”, MIT Press, 2007.

[5] R.P. Smith and Steven D. Eppinger, “A predictive model of sequential iteration in engineering design”, Management Science, vol. 43, no. 8, 1997

[6] H. Yavuz, “An integrated approach to the conceptual design and development of an intelligent autonomous mobile robot”, Robotics and Autonomous Systems, vol. 55, no. 6, pp. 498-512, 2007.

[7] T. Fong, I. Nourbakhsh, and K. Dautenhahn, “A survey of socially interactive robots,” Robotics and Autonomous Systems, vol. 42, pp. 143-166, 2003.

[8] B.Duffy, “Anthropomorphism and the social robot,” Robotics and Autonomous Systems, 2003.

[9] M. MacLin, “The criminal stereotype”, North American Journal of Psychology, vol. 8, no. 2, pp. 197-208, 2006.

[10] S. Kiesler and J. Goetz, “Mental Models and Cooperation with Robotic Assistants”, Proceedings, Conference on Human Factors in Computing Systems, 2002

[11] J. Schulte and C. Rosenberg, “Spontaneous, short-term interaction with mobile robots”, Robotics and Automation,, vol. 1, pp. 658-663, 1999.

[12] A. Green, H. Huttenrauch, and M. Norman, “User centered design for intelligent service robots”, Robot and Human, 2000.

[13] C. Breazeal, “Toward sociable robots”, Robotics and Autonomous Systems, vol. 42, no. 3–4, pp. 167-175, Mar. 2003.

[14] E. Guizzo, “David Hanson’s Incredible Robot Heads”, IEEE Spectrum, 2011