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Lessons learned from robotic vacuum cleaners entering the home ecosystem☆

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HIGHLIGHTS

- This research highlights synergies from two orthogonal studies on domestic robots.
- Energy consumption can benefit from mapping technologies, and influence performance.
- Users' perception and needs are not sufficiently taken into account in robot design.
- Robots are rejected due to incompatibilities with the user's ecosystem.
- Several ways to improve the current state of the art are proposed.

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ABSTRACT

This article considers the suitability of current robots designed to assist humans in accomplishing their daily domestic tasks. With several million units sold worldwide, robotic vacuum cleaners are currently the figurehead in this field. As such, we will use them to investigate the following key question: How does a service cleaning robot perform in a real household? One must consider not just how well a robot accomplishes its task, but also how well it integrates inside the user's space and perception. We took a holistic approach to addressing these topics by combining two studies in order to build a common ground. In the first of these studies, we analyzed a sample of seven robots to identify the influence of key technologies, such as the navigation system, on technical performance. In the second study, we conducted an ethnographic study within nine households to identify users' needs. This innovative approach enables us to recommend a number of concrete improvements aimed at fulfilling users' needs by leveraging current technologies to reach new possibilities.

1. Introduction

Since the early 1950s, futuristic scenarios of our daily lives at home have included robots: robot maids, robot companions, robot nannies, robot guards [1]. This vision has not substantially changed, and it was only a few years ago that Bill Gates predicted in Scientific American that there will soon be "a robot in every home" [2]. Where are we now, however? So far, the only success of domestic robots can be noted in the field of floor-cleaning robots; millions of these devices are used to vacuum people's homes nowadays. We do not know much yet about the long-term acceptance of domestic robots, but first exploratory studies carried out with robotic vacuum cleaners in the United States [3–5] suggest that these devices have several shortcomings that may restrict a broad user acceptance beyond initial adoption. Also, there are strong novelty effects with innovative technologies such as robots [6,7].

Today's robotic technologies are mainly driven by the technical challenges arising when a mobile robot has to perform a specific task in a loosely defined environment. However, some other topics have long been neglected in the design of robots for specific purposes, including the energy-use implications of some technical choices or harmonious integration of the robot into the user's ecosystem [8]. With technological progress, robotic vacuum cleaners (along with other domestic appliances) are now becoming widely available. The time has come to take these topics into

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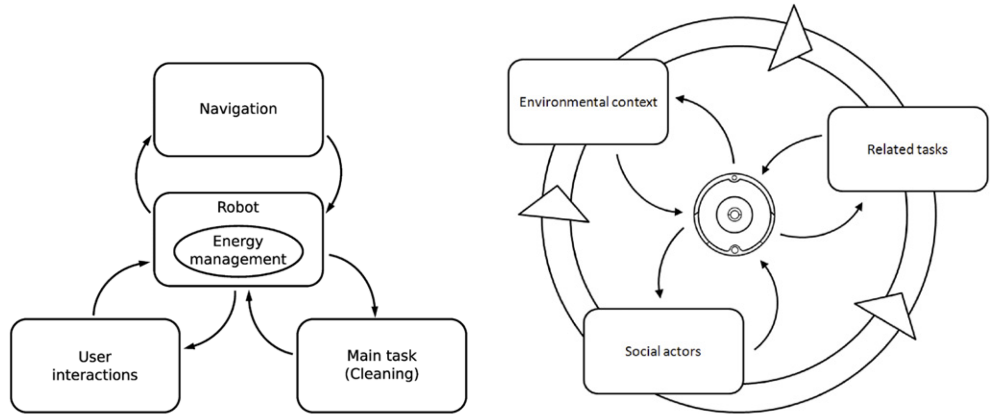

(a) Energetic agent. (b) Social agent.

Fig. 1. Our dual view of the domestic robotic agent. The agent in (a) spends its energy on an number of functions, in order to fulfil its task, and these functions in turn influence the energy consumption. The agent in (b) interacts with several elements that compose its environment.

account when considering the design of future robots, as it appears essential to integrate the user into the design loop to advance these products further.

In robotics today (in spite of a cross-disciplinary approach), the main body of the current research addresses either technical issues (perception, locomotion, or learning algorithms, just to name a few) or social phenomena independently of each other. The effectiveness of the research being performed across disciplines is muted by this process. The technical and user points of view are seldom presented side by side. Our two-sided study fills this gap.

Our approach to these issues tries to be holistic and seeks synergies between current technical research and design that is acceptable for the user. For this, we integrate results from a first technical study on several robotic vacuum cleaners [9] with findings from a second study conducted in people's homes. In doing so, we aim to advance personal robotics from both technical and user-oriented points of view. This collaborative approach brings together research from various fields.

Robotics is, by its nature, multi-disciplinary. With our proposed approach, we aim to extend the borders of the robotic community by showing how synergies can create meaningful cross-disciplinary dialog. Ultimately, the common goal is to develop human-oriented domestic robots that enable meaningful human–robot interaction (HRI) and have the potential to improve people's quality of life.

The remainder of the paper is organized as follows. In Section 2, we will state the main questions guiding both the technical and user studies. Section 3 will list related work to determine the state of the art in both fields, while Section 4 summarizes our dual methodology. The results build the core of Section 5, and they will be presented using a unified outline, raising the knowledge gained up to a higher level. The conclusion of Section 6 will present the analysis of current robotic vacuum cleaners in light of both studies' findings, and will summarize current shortcomings. In this section, we also suggest research directions for leveraging current technologies to enhance user acceptance with targeted improvements.

2. Motivation

Robotic vacuum cleaners have attained a fair degree of success in the domestic robot market. The iRobot Corporation (one of the main players in this market) claims to have sold 6 million units of its "Roomba"robot between 2002 (its first release) and 2010 [10]. According to the statistics of the International Federation of Robotics [11], about 2.5 million personal and service robots were sold in 2011, an increase of 15% in numbers (19% in value) compared to 2010. The forecast for the period 2012–2015 exceeds 10 million units. This trend clearly emphasizes the growing impact of domestic robots in our homes, which creates new interaction paradigms. In parallel, the energy demand for the operation of millions of new cleaning robots will follow the same tendency.

Moreover, with the evolution of technologies, domestic robots shifted from the simple "random-walk" approach towards more evolved navigation schemes, involving a localization technology at an affordable price. Up to now, no scientific study has analyzed the potential impact of these newer robots in terms of user acceptance or energy consumption.

We have carried out two distinct but complementary studies in the present work. The remainder of this section summarizes the questions at the center of both studies, and the contributions gained by linking them together.

2.1. Designing efficient domestic robots

The primary part of this study analyzes the current state of the art and level of achievement in domestic robotics, with a focus on robotic vacuum cleaner and energy-related topics. The robot must have several capabilities in order to fulfil its task: (1) a navigation strategy inside the environment, (2) a cleaning device, and (3) some kind of interaction with the user, at least to start and stop the cleaning process. An energy storage and management unit powers these functions. This view is illustrated in Fig. 1(a). As the energy is located at the center of this robotic system, we will refer to it as an *energetic agent* in the course of this work.

Some research results and design choices for the various functions will impact the energy consumption of the mobile system, and thus affect its autonomy. Within this study, we aim to highlight the influence of these choices on energy consumption, in order to design energy-wise agents that are compatible with a sustainable growth of the number of robots. As we will see, localization and navigation strategies are the main energy savers, and they also bring some other benefits, but more could be achieved by adding better planning and learning. Minimization of energy consumption for robotic vacuum cleaners (and other robots) is an important topic for consideration, especially with the growth of mass-market demands and society's dependence on energy.

This paper presents an analysis of the performance of several existing robots, assessing the impact of the embedded technologies on the system's fulfillments. We present the results from a three-month study performed on a sample of seven robots, bringing together the main trends on the market. The focus is on technical metrics and therefore concerns mostly short-term issues,