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The demand-driven conceptual design of multi-function modular cabinet for medical delivery robot

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Abstract

This paper presents a novel application of the Axiomatic Design (AD) theory to an innovative medical device. A multi-function modular cabinet for medical delivery is designed to deliver various medical supplies simultaneously in consideration of the multi-function delivery demands of typical surgical instruments, organs, drugs, and fluid at modern hospitals. Said demands for medical supplies are systematically analyzed, and four components are established: heating system, cooling system, humidifying system, and dehumidifying system which altogether ensure dynamic balance so as to achieve an uncoupled heat preservation and humidity retention system that meets various delivery demands. By using the multi-function modular cabinet design to build a prototypical medical delivery robot, the proposed technique is proven capable of multi-function delivery and medical resource conservation.

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1. Introduction

Axiomatic design (AD) theory, as first proposed by Suh at MIT in 1990 [1,2], is a cross-disciplinary framework suitable to describing the design and decomposition processes of a wide array of products [3]. Its application makes design goals clear and concise in the initial stages of production [4]. In the present study, the zig-zag mapping method was adopted to verify the accuracy of the design at each stage of the process and to elucidate the corresponding FRs and DPs. AD minimizes any potential mistakes in the product development process and truncates the time necessary to complete the design; AD theory has been widely applied to product design [5,6], system design [7,8,9], software design [10,11], industrial design [12,13], and other fields; in short, it is a successful and well-accepted theory. Design concepts are fundamentally important in terms of developing innovative medical products [14,15]. In this study, we comprehensively analyzed the functions and structures of an innovative drug delivery system with a special focus on AD theory.

In 1983, Joseph Engelberger founded the TRC company to develop service robots. The first product was a medical delivery robot called Helpmate, an autonomous robot which could complete several tasks including the delivery of medical equipment and facilities, medical records, drugs, mail, and packages [16]. In September 2004, a medical center began to use a medical delivery robot in the Mississippi Delta called "EMMA", an acronym for "electronic materials management associate", which could transport drugs, food, experimental samples, and other items [17]. In 2002, Panasonic Corp began to build an intelligent hospital errands robot, HOSPI, with Shiga University of Medical Science [18] which could replace human assistants in transmitting X-rays, samples, and drugs.

At the peak of the SARS outbreak in May 2003, Harbin Engineering University developed a medical robot capable of disinfecting hospital wards and medical equipment; the system had a maximum delivery weight of up to 35 kg [19]. The Institute of Automation of the Chinese Academy of Sciences (CASIA) developed a "SARS assistant" robot that can not only replace medical staff in performing ward rounds, delivering medicine, and administering meals and other

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goods, but can also assist staff in transporting medical equipment, experimental samples, and garbage.

In summary, there certainly have been valuable contributions to the literature in regards to the design of medical delivery robots. To date, however, AD theory has not been used to systematically and comprehensively design this type of robotic system. This study was conducted to explore the conceptual design of a multi-function modular cabinet for delivering medical supplies. The process described here may prove helpful in guiding the practical application of AD theory in the context of medical device design.

2. Demand for multi-function modular cabinet conceptual design

The number of hospitals (and indeed, patients) in the world has been continually increasing on a yearly basis across the world; the number of China's hospitals, for example, is growing by almost 5% per year while the number of patients has grown at a remarkable rate, averaging almost 10% per year. As of the end of May 2015, the number of hospitals in China increased to 26,000. Further, from January 2006 to December 2010, the number of medical accidents due to staff negligence in these hospitals was as high as 98 cases. To this effect, the medical delivery robot represents significant potential for improving hospital services. In addition, the limited space for hospital facilities means that novel drug delivery services have significant profit-earning potential.

Delivery conditions differ across various medical demands. The cabinet volume, sanitation environment, delivery temperature, and delivery humidity must be carefully considered when designing this type of system. The delivery conditions for surgical instruments, organs for transplant, drugs, blood, and food are shown in Table 1; among them, there are strict requirements for temperature and humidity. For example, the temperature requirement for organ transport is generally 0-4°C while that of blood is generally 2-8°C. Surgical instruments and drugs can be divided into three categories: Low temperature (2-10°C), shade (below 20°C), and normal atmospheric temperature (below 30°C). The temperature requirement for delivering food is generally up to 40-56°C. The humidity requirements for delivering surgical instruments, organs, drugs and blood are relatively consistent, about 45%-75%, and the humidity requirement for food fairly negligible.

Medical supplies are generally delivered manually, so real-time delivery cannot be guaranteed. In theory, a robotic, multi-functional modular cabinet for medical supplies delivery would substantially improve the efficiency of hospital operations and reduce the pressure placed on medical staff. For this reason, the present study has important theoretical significance and practical implications.

3. Functional decomposition of modular cabinet based on AD

Based on the requirements for any successful robotic, multi-function delivery cabinet, AD theory was adopted in this study to establish the high-level mapping relationships between FRs and DPs as shown in Table 2.

Table 2 Highest-level functional requirements and design parameters

FRs	Functional requirements	DPs	Design parameters
FR_1	Appropriate delivery environment	DP_1	Modular cabinet
FR_2	Security	DP_2	Password for delivery box

At the highest level of functional decomposition, the constraints of cost, size, weight, and reliability are as shown in Table 3. Cost is the primary factor in the design process and the design of a medical delivery robot is no exception. The robot also must function properly in real hospital conditions, so the size and weight of DP_1 has specific requirements. It is also important to consider the fact that if medical demands are taken by mistake, there may be security risks. Under such conditions, the design reliability of DP_2 is a crucial constraint.

This study mainly focuses on the analysis of FR_1 and DP_1. The conceptual design of a novel modular cabinet is considered according to a realistic delivery environment for various demands. Because DP_1 has been determined on the highest layer, the FRs on the second layer were obtained through corresponding analysis; DPs were determined based on the FRs, as shown in Table 4.

In this layer of the functional decomposition, the constraints necessary to consider are shown in Table 5. To ensure that medical supplies are maintained at the appropriate temperature, C_{11} needs to be ensured first; secondly, C_{12} directly determines the effectiveness of DP_{13}. The shorter the cycle length, the higher the efficiency. Similarly, C_{13} is directly related to whether supplies are delivered at the appropriate delivery humidity. The effectiveness of DP_{14} directly depends on C_{14}. The shorter the cycle length, the higher the efficiency.

Table. 1. Delivery conditions for different delivery tasks

Delivery category	Volume	Sanitation	Temperature	Humidity	Security
Organs for transplant	Dependent on the specific delivery volume	Closed, clean, sterile	Generally 0-4 ℃	Generally 55%-75%	Password for delivery box
Blood			Generally 2-8℃		
Surgical instruments			Low temperature 2-10℃ Shade below 20℃ Normal atmospheric temperature below 30℃	Generally 45%-55%	
Drugs					
Food			Generally 40-56℃	Do not require	