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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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Keywords: Axiomatic Design; Demand driven; Conceptual design; Modular

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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℃	Generally 45%-55%	
Drugs			Normal atmospheric temperature below 30℃		
Food			Generally 40-56℃	Do not require	

Table. 3. Constraint Cs

Constraint	Description	Limitation: FRs	
		FR_1	FR_2
C_1	Cost	—	—
C_2	Size	—	
C_3	Weight	—	
C_4	Reliability		—

Table. 4. Decomposition of FR_1 and DP_1

FRs	Functional requirements	DPs	Design parameters
FR_{11}	Appropriate delivery volume	DP_{11}	Design of multi-size cabinet
FR_{12}	Aseptic environment	DP_{12}	A closed-type cabinet to ensure cleanness and sterility
FR_{13}	Appropriate delivery temperature	DP_{13}	Heat preservation system for temperature requirements
FR_{14}	Appropriate delivery humidity	DP_{14}	Humidity retention system for normal-range humidity

Table. 5. constraint C_1

Constraint	Description	Limitation: FRs			
		FR_{11}	FR_{12}	FR_{13}	FR_{14}
C_{11}	Temperature measurement accuracy			—	
C_{12}	Temperature control cycle time			—	
C_{13}	Humidity measurement accuracy				—
C_{14}	Humidity control cycle time				—

After the corresponding DPs are acquired, the effects of DPs on FRs should be analyzed. It is important to account for the fact that when the absolute humidity is constant, an increase in temperature causes relative humidity to decrease. When the temperature drops, the relative humidity is bound to rise. When the relative humidity is constant, absolute humidity increases as temperature increases; when the temperature drops, absolute humidity will inevitably drop as well.

Through heating and cooling, DP_{13} not only satisfies FR_{13} but also affects FR_{14}. Traditional humidification is controlled by heating and cooling, so when DP_{14} ensures FR_{14}, it also affects FR_{13}. That is to say, DP_{13} and DP_{14} have cross effects on FR_{13} and FR_{14}. The design matrix shown below is not a diagonal matrix or a triangular matrix – it is a decoupled design.

$$\begin{bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \\ FR_{14} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & X \\ 0 & 0 & X & X \end{bmatrix} \begin{bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \\ DP_{14} \end{bmatrix} \tag{1}$$

At present, medical supplies are typically delivered 100% manually in most hospitals. The delivery period is generally very brief, so it is not necessary to regulate the temperature and humidity of the supplies being delivered. As hospitals trend towards automation, the delivery requirements of medical supplies will be improved as they are more “intelligently” delivered. Under the AD theory, the focus of this study was to ensure the constant temperature and humidity of the delivery cabinet. This necessitated further decompositions for DP_{13} and DP_{14}, as shown in Table 6 and Table 7.

Table. 6. Decomposition of FR_{13} and DP_{13}

FRs	Functional requirements	DPs	Design parameters
FR_{131}	Temperature detection	DP_{131}	Temperature detection system
FR_{132}	Heating	DP_{132}	Heating system
FR_{133}	Cooling	DP_{133}	Cooling system

DP_{13} consists of the following three parts: The temperature detection system, heating system, and cooling system. DP_{131} monitors the changes in system temperature real-time. DP_{132} raises the system temperature as-necessary with the heater, while DP_{133} reduces system temperature as-necessary with the compressor.

In DP_{132}, once a controller receives the command, the heat is elevated in the cabinet via the wind turbine until the cabinet’s interior reaches the desired value. In DP_{133}, the compressor brings in low-temperature and low-pressure gas. which is put into a high-temperature and high-pressure state, condensed into liquid, released as heat through a blower, then converted back to low-temperature and low-pressure gas through the evaporator and back into the compressor to cool the cabinet. The heat preservation system itself does not feature any functional coupling. It works to reach a dynamic balance and maintain a constant temperature in the cabinet. The design matrix shown below is a diagonal matrix.

$$\begin{bmatrix} FR_{131} \\ FR_{132} \\ FR_{133} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP_{131} \\ DP_{132} \\ DP_{133} \end{bmatrix} \tag{2}$$

Table. 7. Decomposition of FR_{14} and DP_{14}

FRs	Functional requirements	DPs	Design parameters
FR_{141}	Humidity detection	DP_{141}	Humidity detection system
FR_{142}	Spray and humidify	DP_{142}	Humidifying system
FR_{143}	Inhale and dry	DP_{143}	Dehumidifying system

DP_{14} includes three parts: The humidity detection system, humidifying system, and drying system. DP_{141} measures humidity in real time. DP_{142} increases the humidity through the high-frequency oscillation of an ultrasonic wave; this turns water to mist which is spread through the cabinet through a pneumatic device. In turn, DP_{143} decreases the humidity through the refrigeration cycle in which the temperature is adjustable. Air first passes through the evaporator and is cooled, then part of the condensing heat is carried away by the air-cooled condenser while the remaining condensing heat is used to heat the air through the evaporator. Eventually, this changes the temperature of the circulating air in accordance with the temperature inside the cabinet. The dynamic balance achieved via this process ensures constant humidity. The humidity retention system itself also does not have functional coupling, so its design matrix is also a diagonal matrix.

$$\begin{bmatrix} FR_{141} \\ FR_{142} \\ FR_{143} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP_{141} \\ DP_{142} \\ DP_{143} \end{bmatrix} \tag{3}$$

In conclusion, in order to decompose DP_{13} and DP_{14}, four systems (heating system, cooling system, humidifying system, and dehumidifying system) were introduced through the design of DP_{132}, DP_{133}, DP_{142} and DP_{143}. Based on the AD theory, the effect of DP_{142} on DP_{132} and the effect of DP_{143} on DP_{133} were eliminated by redesigning the functional structure as shown in Figure 1.

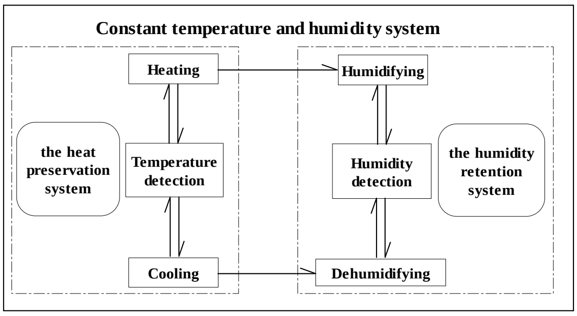


Fig. 1. Constant temperature and humidity system design

In order to establish a constant temperature and humidity delivery environment, the coupling effect of DP_{14} on DP_{13} was removed. The cross effects of DP_{13} and DP_{14} on FR_{13} and FR_{14} were then eliminated to solve the coupling problem. Finally, a triangular 8×8 design matrix was obtained, through which the design scheme meets the independence axiom well and is a decoupled design.

Table. 8. Function structure design matrix

Functional	Design Parameters							
Requirements	DP_{11}	DP_{12}	DP_{131}	DP_{132}	DP_{133}	DP_{141}	DP_{142}	DP_{143}
FR_{11}	X							
FR_{12}		X						
FR_{131}			X					
FR_{132}				X				
FR_{133}					X			
FR_{141}						X		
FR_{142}				X			X	
FR_{143}					X			X

4. Multi-functional modular cabinet design concept

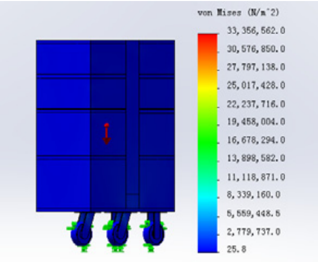
(a) (b)

Fig. 2. Multi-functional modular cabinet design

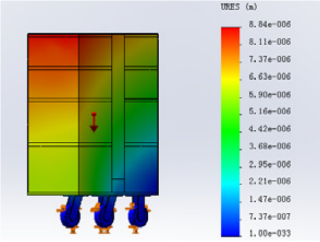
The overall design scheme of the medical delivery robot is shown in Figure 2(a). After careful analysis of the demands of the multi-function modular cabinet, several corresponding functional requirements became clear and feasible design parameters were established accordingly.

The primary focus of this study was analyzing the adjustment of environmental temperature and humidity. The heat preservation and humidity retention systems were set up accordingly in order to meet various delivery demands. Both are modularization units that can be readily, easily assembled according to different delivery needs. An array of delivery cabinets with different sizes were also designed to appropriately account for the different shapes and sizes of medical supplies (Figure 2(b)). The cabinet is enclosed, making it easy to disinfect to maintain a clean and sterile environment for the supplies. The cabinet is also password-protected system to further ensure that the correct supplies are delivered safely to the correct destination. These factors altogether make the proposed scheme "humanized" in nature and well-aligned with the actual application requirements.

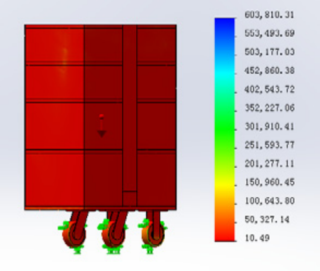
A finite element analysis of the cabinet was conducted once the design was complete, as shown in Figure 3. The stress and strain are within the yield limits and the safety factor is far larger than 1, indicating that the design scheme fully meets the necessary demands.



(a) Stress analysis



(b) Strain analysis



(c) Safety factor analysis

Fig. 3. Finite element analysis of delivery cabinet

5. Conclusions

Based on theoretical research and thorough analysis, a new delivery cabinet design scheme was established fully in line with actual delivery requirements for various medical supplies. Under AD theory, the functional requirements of the cabinet were systematically analyzed to determine the corresponding design concepts; this included a detailed function coupling of delivery temperature and delivery humidity which ultimately yielded a triangular 8×8 design matrix. The coupling effect of the humidity retention system on the heat preservation system was eliminated so as to establish a constant temperature and humidity delivery environment. The heat preservation system and humidity retention system were further optimized as modularization units which are easy to assemble according to different delivery needs. The cabinet volume, sanitation environment, and security, which are also of critical importance, were also designed appropriately. To sum up, this paper has presented a well-structured application of AD theory in the context of medical device design for hospital customers.

In building the constant temperature and humidity delivery environment, the design of the humidity retention system was optimized based on AD theory so as to eliminate the effect of humidifying on heating and the effect of dehumidifying on cooling. In future research, the heat preservation system design will be optimized in order to eliminate the effect of heating on humidifying and the effect of cooling on drying. In this way, the design of the delivery cabinet will become fully uncoupled.

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