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協助照護臥床病人的氣墊系統開發

Development of Air Mattress System for Assisting Cares to
Bedridden Patients



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摘要

臥床不起意味著失去行動能力和獨立性。對於臥床不起的患者和照護者來說，進行一些日常生活活動是具挑戰性的。為了克服這些挑戰，本研究提出一種創新方法，旨在透過依序控制多室充氣床墊的鄰接氣室的充氣狀態，並採用獨特控制技巧，來協助臥床病人穿脫衣褲。這項研究比較了建議方法和傳統方法在執行上述活動期間患者的運動點和身體負擔。擦拭身體的實驗顯示，本研究提出的方法能顯著減少僅在清潔腋下時需要改變體位的需要。使用便盆和更換尿布的實驗顯示，在一維充氣床墊上調整腿部至所需位置所需的體位變換最少。對於使用所提出方法協助更換褲子的實驗表明，無需對患者進行手動體位調整。護理人員只需透過簡單動作穿上褲子，無需承受患者體重的壓力。此外，在更換襯衫、T 恤和 A-Line 長衫時，護理人員僅需移動患者的手。實驗結果顯示，相較於傳統方法，本文所提出的方法在減少所需的體位變換方面表現明顯更好。根據進行日常生活活動時僅需要最少的體位變換，也證明本研究所提出的解決方案能夠極大地提高患者舒適度並減輕護理人員的負擔。

關鍵字: 醫用充氣床墊、長期臥床、照護者、照護、日常生活動作

ABSTRACT

Being bed-bound means loss of mobility and independence. Some active daily living tasks are challenging for bedridden patients and caregivers. To overcome these challenges, a novel approach aims to assist active daily living for the bedridden by sequentially controlling the inflation status of each chamber's row of multichambered air mattresses and performing a unique control technique. The study compares patients' points of movement and physical burdens during the activity between the proposed and conventional methods. The experiments of dry bathing show that the proposed approach can significantly reduce the need for posture change that is only to be performed to clean the armpit. The bedpan and diaper change indicate that minimum posture change is required on a one-dimensional air mattress to sift the leg in the desired position. The experiment for changing pants on the proposed approach shows that no manual posture change is required on the patient. The caregivers only need to put on the pants by simple movement without applying any force against the patient's body weight. Furthermore, the caregiver only needs to move the patient's hand during changes of the shirt, T-shirt, and A-line. The results show that the proposed approach has significantly better results by reducing the required posture changes than conventional methods. Minimum posture changes while conducting ADL prove that the proposed solution can greatly improve patient comfort and reduce caregivers' burden.

Keywords: Medical Air Mattress, Bedridden, Caregiver, Nursing, Active of Daily Living

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CHAPTER 1

INTRODUCTION

1.1 Research Background

By 2050, people over the age of 65 will reach 20% of the global population, and 80% of them will live in low- to middle-income countries. Population aging, with an increasing number of disabled people, has become a significant concern in many countries [1-3]. In addition, developed countries encountered the effects sooner than developing nations. The developed countries most affected include South Korea, Taiwan, Japan, Italy, France, Germany, the UK, and the USA, as depicted in Figure 1-1. In recent years, Taiwan and Korea have had relatively low percentages of aging populations, but it is projected that by 2050, they will experience significant increases, becoming some of the largest aging populations [4]. This trend can be attributed, in part, to the positive impact of health facilities, which have improved overall well-being and longevity. The rapid growth of the elderly population also highlights the increasing need for advanced technology to support their activities, particularly for those who are wheelchair-bound or bedridden.

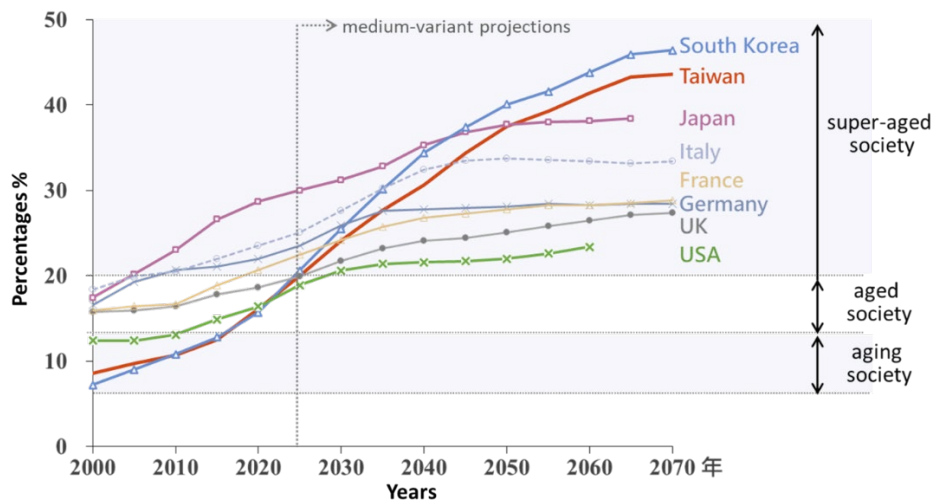


Figure 1-1. Projection of aging population in developed country [4].

The human life cycle is a dynamic journey marked by distinct stages, each characterized by unique physical and psychological changes. One inevitable aspect of this cycle is the process of aging, a natural and universal phenomenon as illustrated in Figure 1-2 . From infancy to old age, individuals undergo transformations that shape their experiences and perspectives. While aging is a normal part of life, it is not without consequences. Physiological changes, such as the gradual decline of physical capabilities and the emergence of health-related challenges, are common occurrences in the later stages of life.

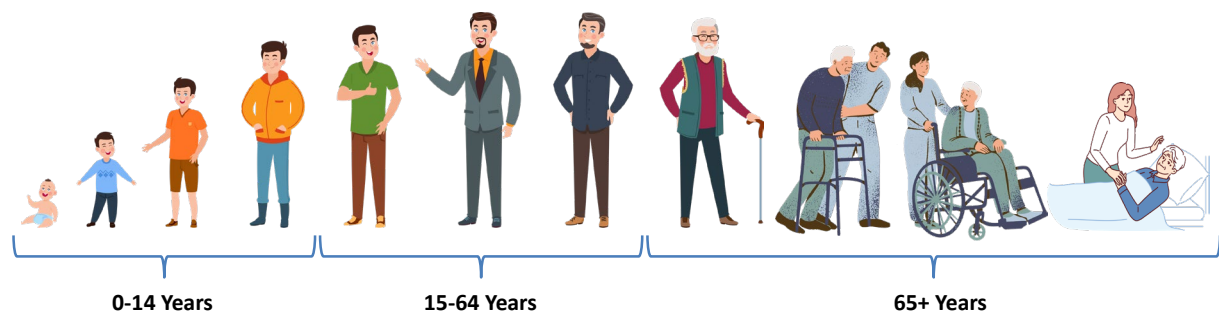


Figure 1-2. The human life cycle spans from birth to over 65 years of age [5-8].

Furthermore, the consequences of rapid aging population growth are complex issues that raise numerous healthcare concerns, including the long-term care of disabled people. An issue associated with an aging population is that a portion of individuals will experience limited mobility, resulting in some being confined to chairs, while others may be partially immobilized and confined to beds as bedridden for the remainder of their lives [9].

Bedridden is a patient's state of health with immobility characterized by the inability to exercise self-care, either partially or totally, and requiring assistance to perform some activities of daily living (ADL) [10]. Several factors cause a person to be bedridden, and aging is the most common reason people are bedridden due to a decline in functional and cognitive capacity [11]. Furthermore, older adults have a high prevalence of severe health conditions that make the time for bed rest come earlier [10, 12, 13]. A brain or spinal cord injury is also one of the reasons why people must spend their lives in bed [14-17]. Another reason is that chronic

diseases such as stroke and neuromuscular disorders are the ones that cause people to stay in bed [18-21]. From the diseases mentioned above, bedridden is considered in expanded disability status scale (EDSS) as the most severe condition level as depicted in Figure 1-3.

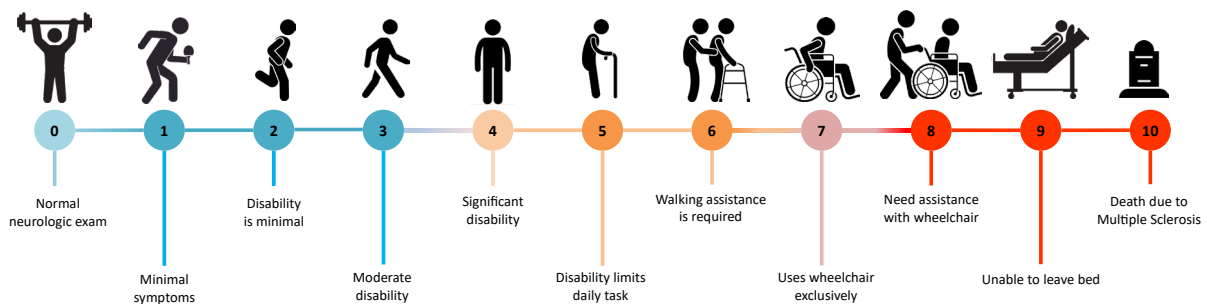


Figure 1-3. Expanded disability status scale.

Being bedridden leads to many complications, such as bedsores and muscle wasting, two of the more serious implications of being immobile [22, 23]. In addition, being confined to a bed can increase the likelihood of developing cardiovascular, respiratory, musculoskeletal, and neuropsychological changes [24].

To assist the bedridden patients, caregivers require adequate knowledge or training to nurture the bedridden patients through everyday tasks. Without proper training, caregivers can quickly become physically and emotionally exhausted due to task difficulty and extended time consumption [25, 26]. Professional caregivers frequently describe lower back discomfort as a major issue due to workloads of manual patient lifting, poor posture, and prolonged work duration during nursing practice [27-29].

Despite their limited mobility, bedridden patients must undergo ADL such as toileting (by changing diapers or using a bedpan), bathing, changing clothes, taking medication, as well as maintaining nutrition and hydration [9, 30]. They must also adjust their body posture regularly, manage pressure on body regions for wound therapy, etc. This daily task is difficult

for bedridden people and those who care for them [25]. Some bedridden patients cannot conduct some or all of their activities without the presence of a caregiver. The care-providing sector provides several solutions to nurse bedridden persons, such as adaptive beds and mattresses [31-33], adaptive clothes [34-36], assistive robots [37], and professional caregivers [38, 39]. Despite these available options, they are still below an ideal level due to functional limitations, and these nursing care tasks are likely heavy burdens for caregivers.

Bathing stands out as a crucial component of ADL for preserving healthy tissues and ensuring the cleanliness of a patient's skin by removing dust and excess oil. The conventional method requires several posture changes to clean the back side of the patient's body [40]. This method creates a complex procedure, requiring caregivers to perform cleaning tasks while maintaining the patient's posture in stable positions like a recumbent position. This intricate process also adds additional discomfort for the patient.

Bedpan changes are a regular task for bedridden patients if they have the ability to control or manage bodily functions, particularly those related to the release of urine or feces [41]. Its routine can be different for each patient according to the patient's condition. The current method of changing bedpans using conventional methods and air mattresses is available on the market [42-44]. The conventional method required lifting the buttock of the patient to put the bedpan properly beneath the buttock of the patient, while the air mattress can provide additional space for the bedpan. However, the air mattress only adds additional space without changing its technique of bedpan change. Both methods involve lifting the patient and adjusting their posture to facilitate the bedpan change. These procedures place a physical burden on the caregiver and may cause discomfort during the bedpan change process. The survey revealed that a significant proportion of caregivers, predominantly family members, faced constraints

on their leisure activities as their schedules were fully dictated by the need for pad changes [41].

Diaper change is required for incontinence patients. In the elderly population, incontinence is a troublesome and common symptom. A previous study revealed that 46–72% of residents in nursing homes experience urinary and/or fecal incontinence. Other reports indicate that the estimated rate of urinary incontinence among individuals older than 65 is approximately 35% for those living in the community but exceeds 60% for those in long-term care facilities. Incontinence poses a significant health challenge for both those in need of nursing care and those providing it. It contributes to the breakdown of the skin in the buttock area. Risk factors for skin breakdown include overhydration, the penetration of stimuli into the skin, higher pH, colonization of microorganisms, friction caused by the cloth (diaper) in an occlusive environment, urine, and fecal matter [41]. These factors can result in skin tears, abrasions, infections, and/or pressure ulcers [45]. Therefore, regular diaper change is important. The traditional approach to changing diapers involves multiple adjustments in posture, and some automated beds only replicate this conventional method. This implies a reduction in the physical burden on caregivers but still results in discomfort for the patient.

In particular, bedridden patients encounter difficulties when it comes to changing clothes as a result of their limited movement. The conventional method in the literature involves undressing and dressing fully dependent elderly people with several types of clothes, which involve multiple posture changes [46-49]. These changes cause discomfort for the bedridden and impose a physical burden on the caregiver. Improper technique during clothes change can also damage the skin due to the force of friction while sliding the clothes over the patient [50]. While assisting the bedridden with clothing change, the caregiver experiences a physical load that may lead to occupational injuries due to the need for multiple posture

adjustments and intricate dressing changes performed in awkward positions after a long period of time [29]. The current sophisticated methods, such as an electric bed and mattress, can reduce the physical burden during posture change by moving the workload to the machine [31, 51-53]. However, the current approach is unable to address the risk of clothing and fails to promote simple clothing techniques for any clothing model.

In addition, adaptive clothing is specifically designed to cater to the unique needs of individuals who are bedridden or have limited mobility. It incorporates innovative design elements that enhance comfort, functionality, and overall well-being. The key advantage of adaptive clothing is its ability to simplify the dressing process for both patients and caregivers [34]. Adaptive clothing addresses the difficulty of clothing with modifications like velcro, magnetic closures, open backs and sides, and pull-on waists to account for limited mobility and dexterity [54]. Nevertheless, adaptive clothes are not generally accessible in many countries, and the market lacks a diverse range of designs and sizes [55].

Therefore, this study aims to overcome the issue of ADL for bedridden patients by reducing excessive posture changes. This can be achieved through the integration of a new multichambered air mattress design, its innovative operational algorithm, and a unique technique to conduct ADL.

1.2 Objectives and Scope of Study

This research aimed to create an advanced medical air mattress featuring multiple chambers and interactive capabilities to enhance the quality of life for bedridden patients while alleviating the physical burden on caregivers. The investigation delved into the conditions and needs of bedridden individuals and their daily activities, examining the impact of nursing care on caregivers. Furthermore, the existing study serves as a benchmark for the proposed solution.

The research presents practical, resilient, and versatile solutions applicable to diverse scenarios.

The thesis is particularly focused on the following objectives:

- i) Development of medical air mattresses with the capability to help bedridden patients to conduct active daily living.
- ii) To design and implement a medical air mattress for dry bathing, bedpan, and diapers change also dressing and undressing bedridden clothes.
- iii) To design and implement a medical air mattress that provides sufficient space for caregivers to perform tasks under bedridden bodies.
- iv) To design and implement a medical air mattress to reduce the burden on caregivers.

1.3 Thesis Structure

The thesis structure is organized as follows: Chapter 1 specifically describes the background and the objective of the study. Chapter 2 describes the literature review and theoretical background that were used in the study. Chapter 3 will show the proposed design and implementation details. Chapter 4 is the result and discussion of the developed prototype. Finally, Chapter 5 presents our conclusions and future work.

CHAPTER 2

LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1 Taiwan Ageing Society

In recent years, Taiwan has experienced a decline in its population, primarily attributed to a low birth rate, as shown in Figure 2-1. The diminished birth rate is directly correlated with the decreasing population of individuals in their productive age [4]. As the productive population decreases, Taiwan will see a loss of its economic driving force. Additionally, Taiwan stands out as one of the nations with top-tier healthcare facilities and services globally, leading to increased life expectancy and a growing population of individuals aged 65 and above.

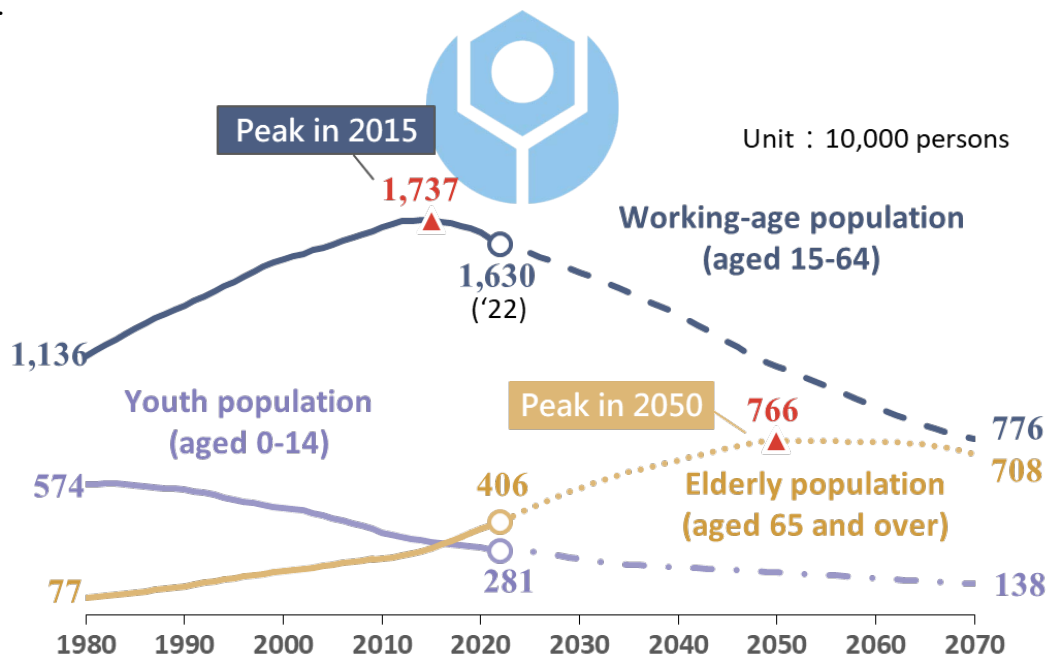


Figure 2-1. Demographic projection structure in Taiwan 2022-2070 [4].

As reported by Taiwan Business Topics, Taiwan is projected to become a super-aged society by 2025, with 20% of its population being over the age of 65. By 2034, it is projected that over 50% of Taiwan's population will consist of individuals aged 50 or older due to the

ongoing decrease in the birth rate [56]. This report is backed by the National Development Council of Taiwan, providing scientific data on the population distribution over three age categories from 1961 to 2063, as represented in Figure 2-2. These categories include individuals aged 0-14, 15-65, and 64+, which represent children, the productive age, and the elderly, respectively. This data shows that Taiwan is now an aged society, starting in 2018, with the aging proportion being more than 14%. In only a couple of years, Taiwan will be a super-aged society by 2025 [4].

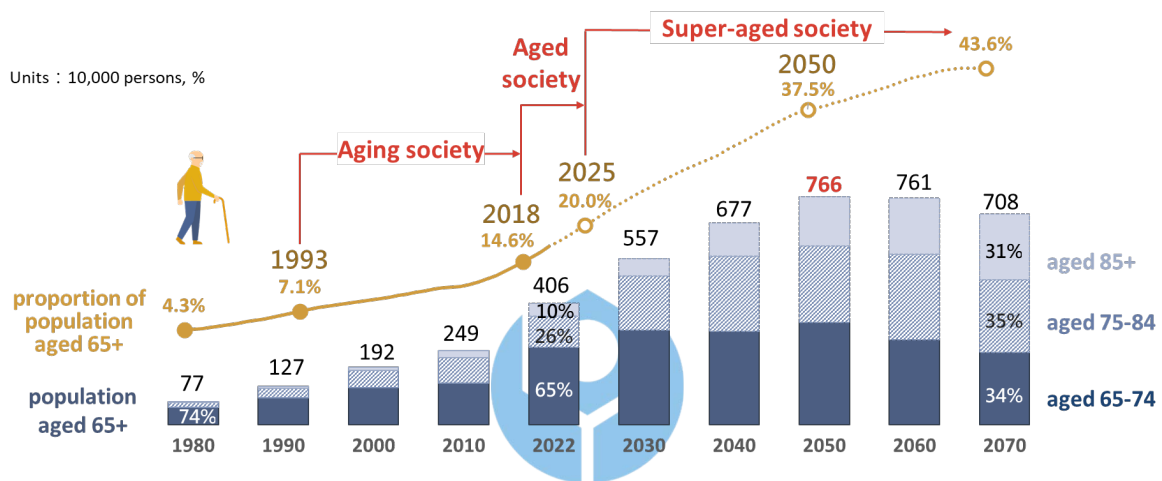
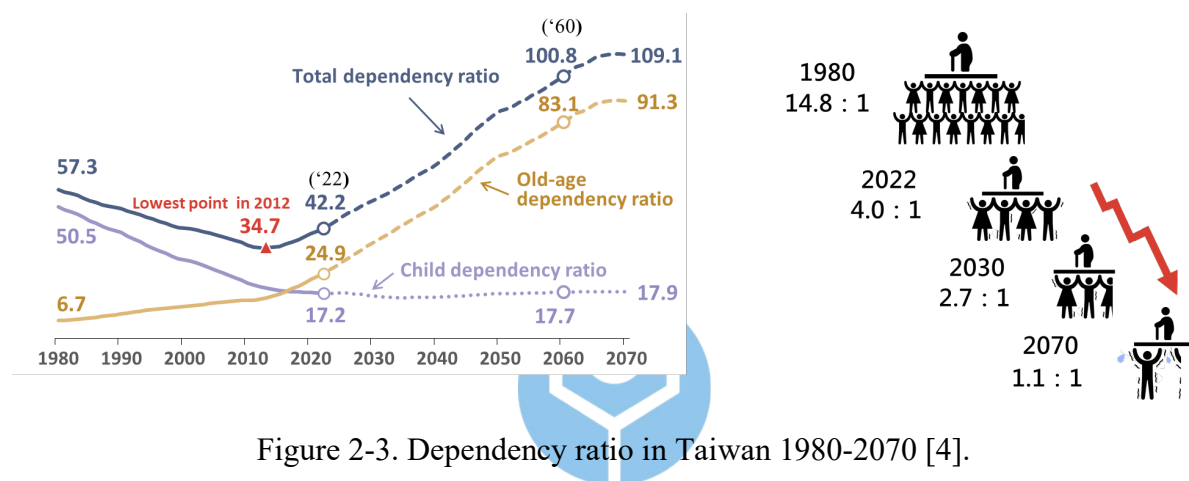


Figure 2-2. Demographic projection structure of aging society in Taiwan 2022-2070 [4].

Furthermore, Taiwan's demographic composition plays a role in determining the dependency ratio, which is associated with the country's burden. Essentially, a high dependency ratio signifies heightened difficulties for individuals in the labor market and the wider economy in supporting an older population. The youth reliance ratio refers to the proportion of individuals aged below 15, whereas the senior dependency ratio specifically targets individuals aged 64 and above. Dependency ratios are frequently examined to evaluate the proportion of the overall population in the working-age bracket who are accountable for providing assistance to the population that is not of working age. This approach functions as a tool for economists to observe and track changes in population characteristics. A favorable dependence ratio is characterized by a low value, which signifies the presence of a substantial

workforce that is capable of providing assistance to the dependent population. Decreased dependency ratios are linked to enhanced healthcare provisions for elderly individuals and more substantial retirement benefits. On the other hand, a high dependence ratio indicates economic pressure, as the number of people who rely on others for assistance is too great to be sufficiently provided for by the working-age population. Based on this information, we can infer that Taiwan's present situation is a cause for concern with a total dependency ratio up to 50%, and it will almost double by 2050, as illustrated in Figure 2-3 [4].



Taiwan must address the challenges related to the rising dependency among the elderly, especially in providing assistance for their daily necessities. This endeavor is vital to mitigating the escalating difficulties encountered by nurses as the age of patients progresses. These concerns are typically known as Active Daily Living (ADL), such as toileting (by changing diapers or using a bedpan), bathing, changing clothes, taking medication, and maintaining nutrition and hydration [9, 30].

Moreover, the traditional approach to ADL involves intricate actions that pose challenges for both the bedridden individual and the caregiver. The first challenge of ADL is giving nutrition and hydration to the bedridden. This daily activity is conducted by reclining

the patient on the mechanical bedframe or reclining air mattress, as shown in Figure 2-4 (a) and (b), respectively. This well-established technique will not be included in our study.

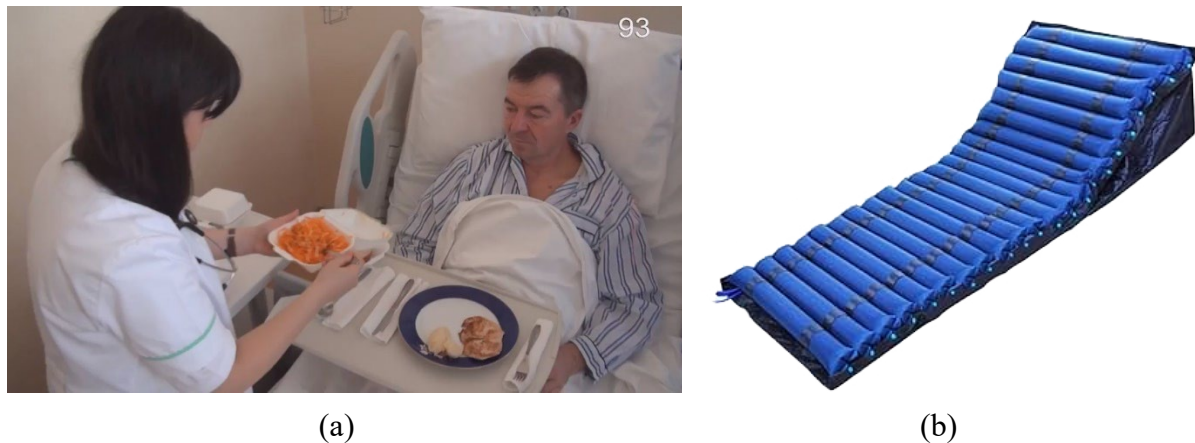


Figure 2-4. Reclining bed system (a) Reclining bedframe [57] (b) Reclining air mattress [57].

Furthermore, one of the important ADLs is bathing, which commonly uses a technique of dry cleaning, as illustrated in Figure 2-5 [40]. Taking care of bathing for bedridden at least conducted by caregiver once each day for hygiene purpose. Proper cleaning can preserves mental health, prevents diseases, prevent skin irritation, and socialize better [58]. The first impression looks easy when the process of cleaning the face of the patients. Then the Figure 2-5 b-h shown necessitates multiple changes in posture to accomplish the task. Even when undertaken by two caregivers, there remains an additional physical burden as they need to reposition the patient into a recumbent position to attend to the cleaning of the patient's back and the changing of clothes, as depicted in Figure 2-5.

In order to wash the patient's hair, the caregiver requires an inflatable shampoo basin as shown in Figure 2-6 [40]. The demonstration, however, does not illustrate the process of placing the basin on the patient's head. The head must be elevated to affix the basin. Following that, the caregiver simply has to carry out hair cleaning, involving wetting, shampooing, and subsequently rinsing and drying, as one would with a person not facing mobility challenges.

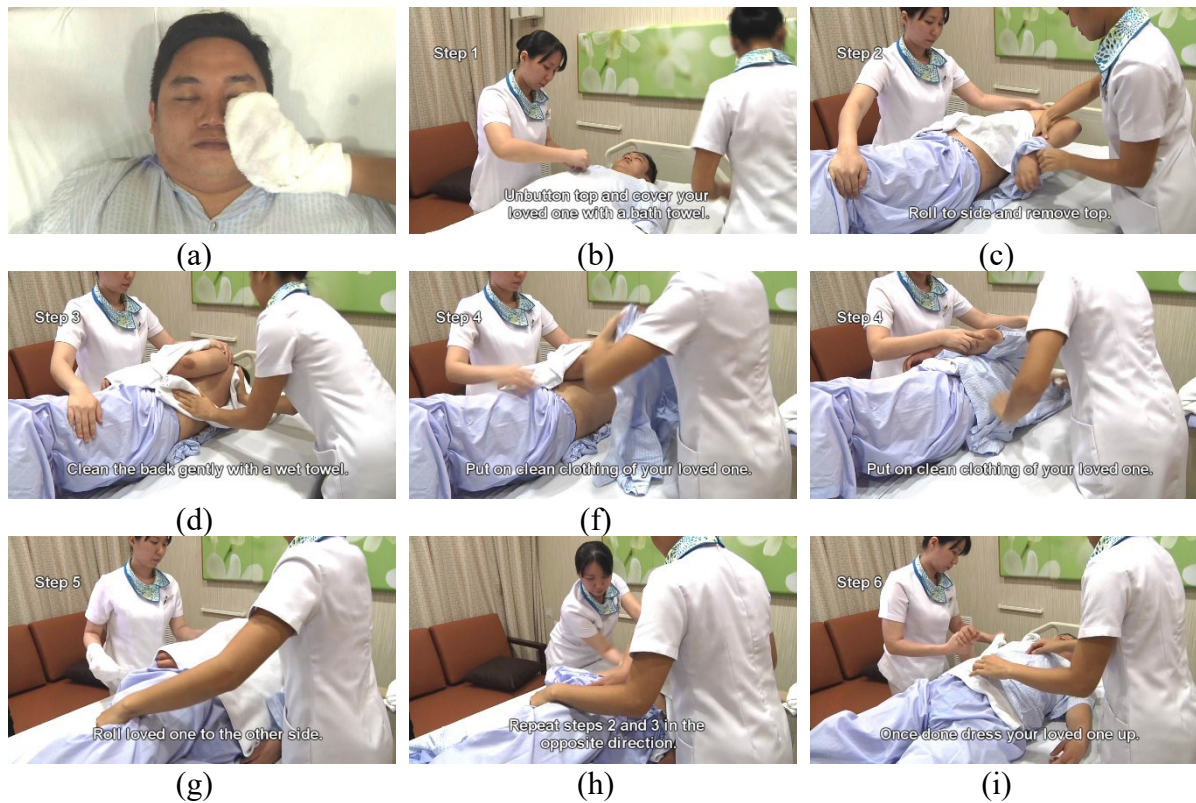


Figure 2-5. Process of conventional bathing [40].

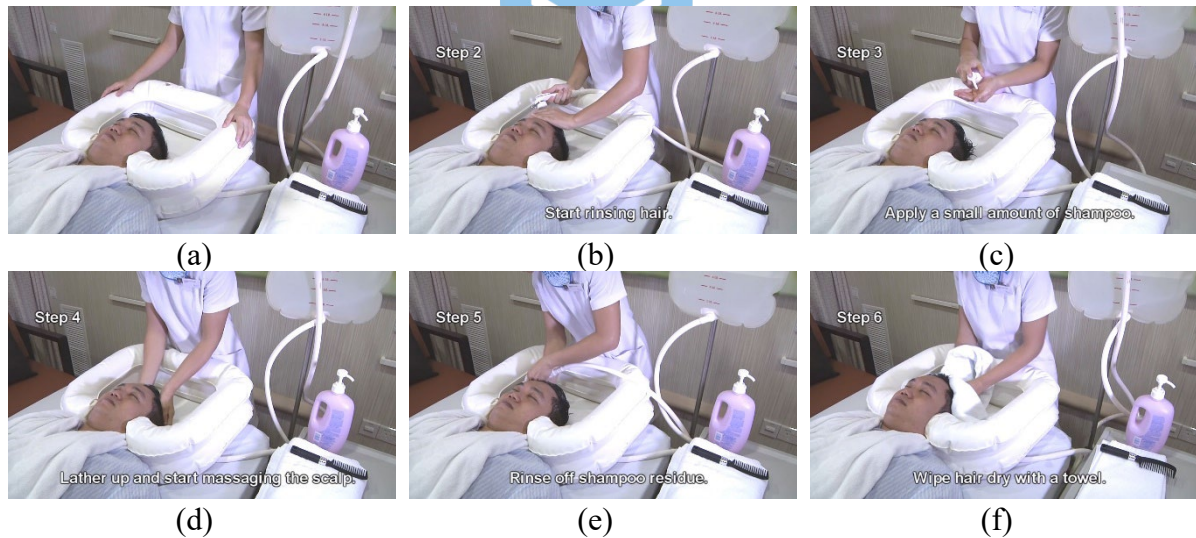


Figure 2-6. Process of conventional hair cleaning [40].

Another supplementary obstacle arises during the diaper change, as depicted in Figure 2-7. The process involves adjusting one's posture to remove both upper and lower clothing. Subsequently, removing the diaper while cleaning the buttocks for a period of time (Figure 2-7

c-f) adds an additional physical burden. Even the act of putting on a new diaper and dressing necessitates certain posture changes, leading to mental exhaustion (Figure 2-7 g-l) [59].

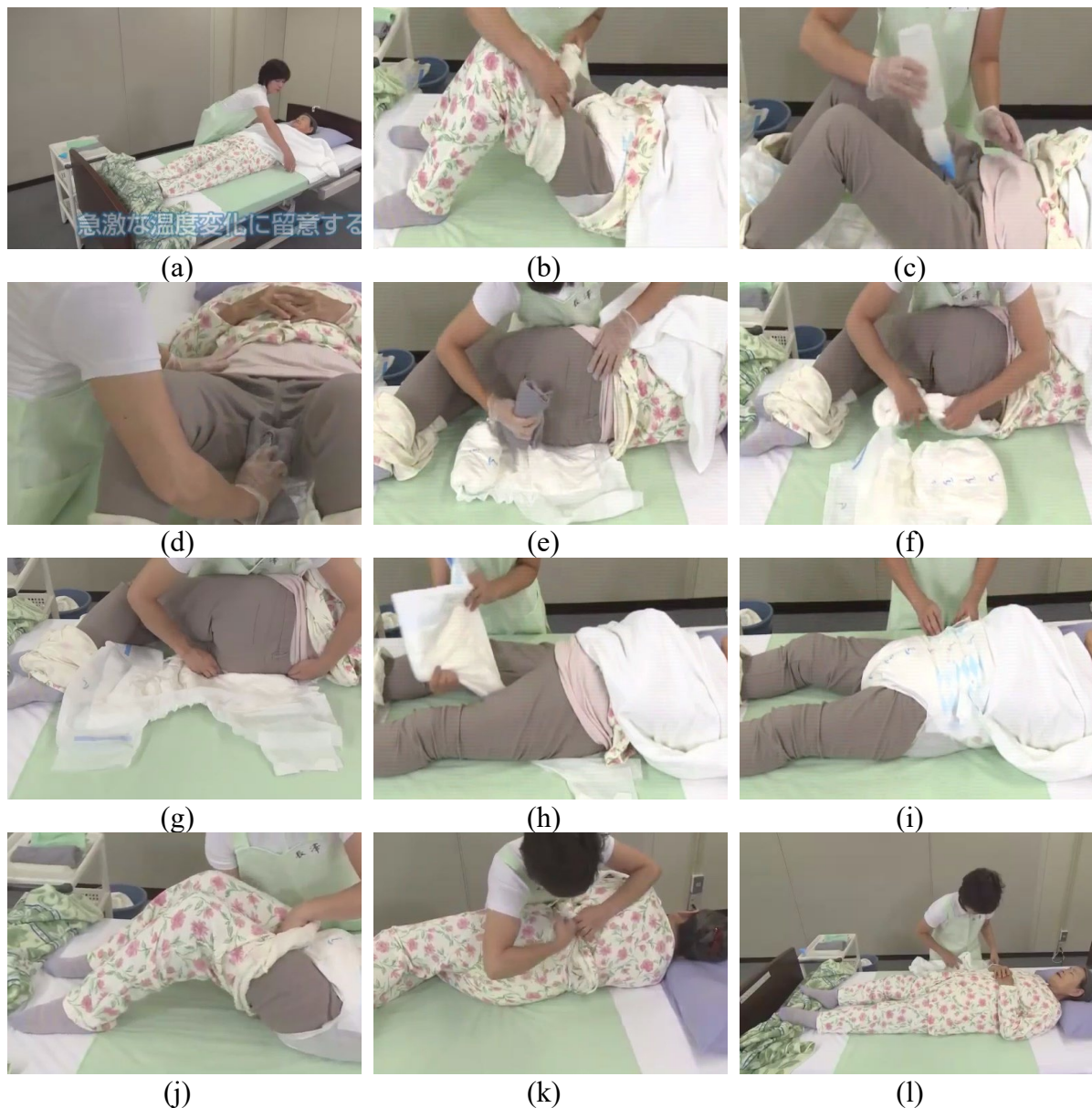


Figure 2-7. Process of conventional diaper replacements [59].

For the patient which does have incontinence problem, a bed pan is daily routine for defecation and urinary. The process of bedpan change is quite similar with the diaper change which require several posture adjustments as shown in Figure 2-8 [60].



Figure 2-8. Process of conventional changing bedpan [60].

Figure 2-9 illustrates the technique employed by a skillful caregiver to simultaneously undress and dress the patient's shirt. This technique is particularly effective because the methods for dressing and undressing in the conventional approach are identical and do not involve any cleaning steps. In a typical scenario, the caregiver can efficiently and quickly change the patient's shirt without interruption, as the simultaneous technique leverages the uniformity of the dressing and undressing processes. This method is advantageous in situations where speed and simplicity are prioritized, especially when the patient is in a stable condition and no additional care tasks are required. However, if cleaning or other care activities are necessary during the clothing change, the process becomes more complex. For instance, if the patient needs to be cleaned before putting on a fresh shirt, the caregiver must interrupt the clothing change to perform the cleaning. This interruption prevents the use of the simultaneous dressing and undressing technique. Instead, the caregiver must follow a step-by-step approach:

first undressing the patient, then performing the required cleaning, and finally dressing the patient in clean clothes. This ensures proper hygiene and patient care but takes more time and effort compared to the simultaneous method.

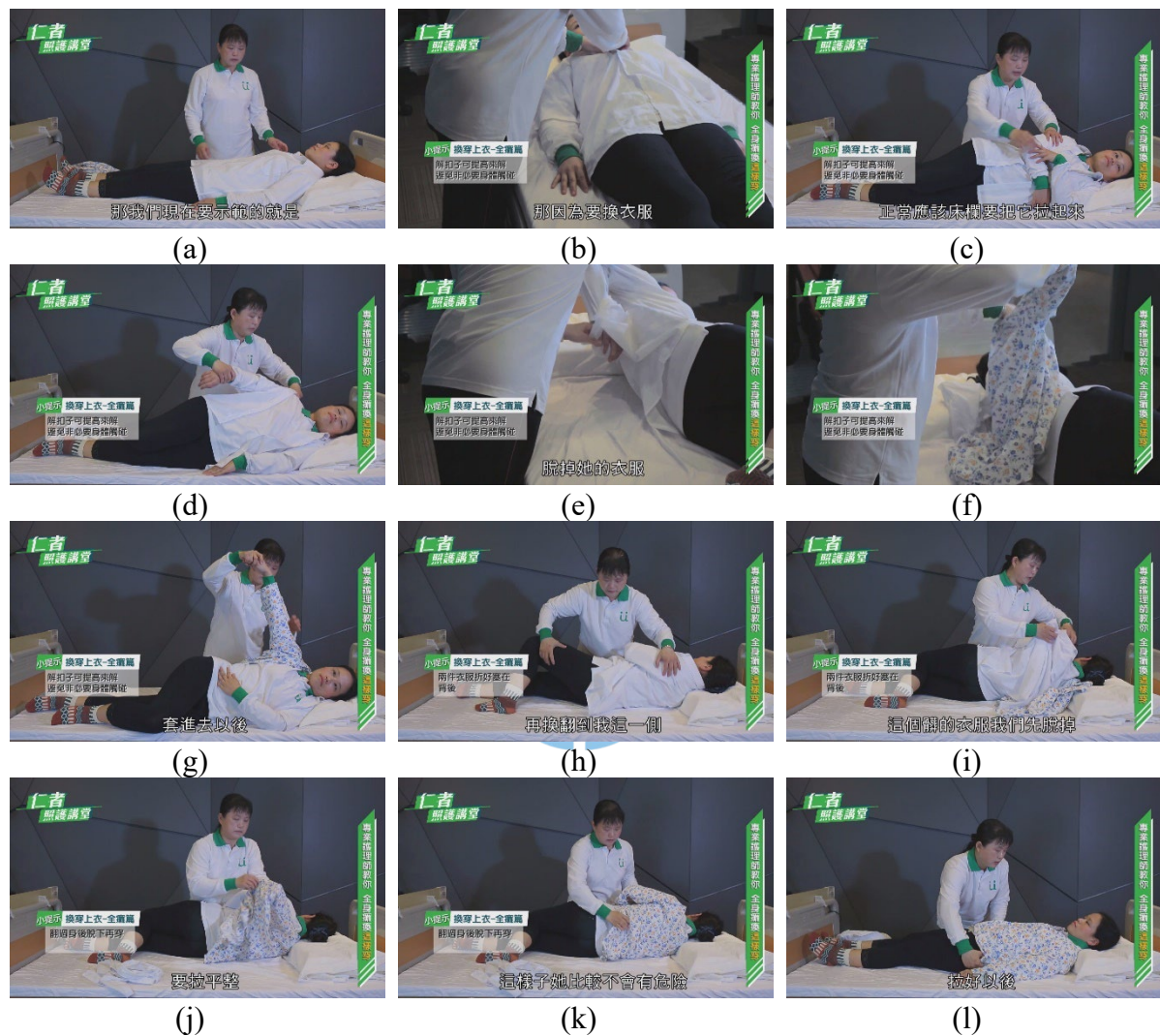


Figure 2-9. Process of conventional changing shirt [46].

Furthermore, on Figure 2-10 show the skillful caregiver who can undress and dress the patient's pants at once. This technique is similar to the previous shirt change while there is no cleaning process performed. Even for changing a pair of pants which are simple clothes to cover lower limb of bedridden patients, the patient needs to be repositioned several times. Its inefficient technique can lead to caregiver physical load.

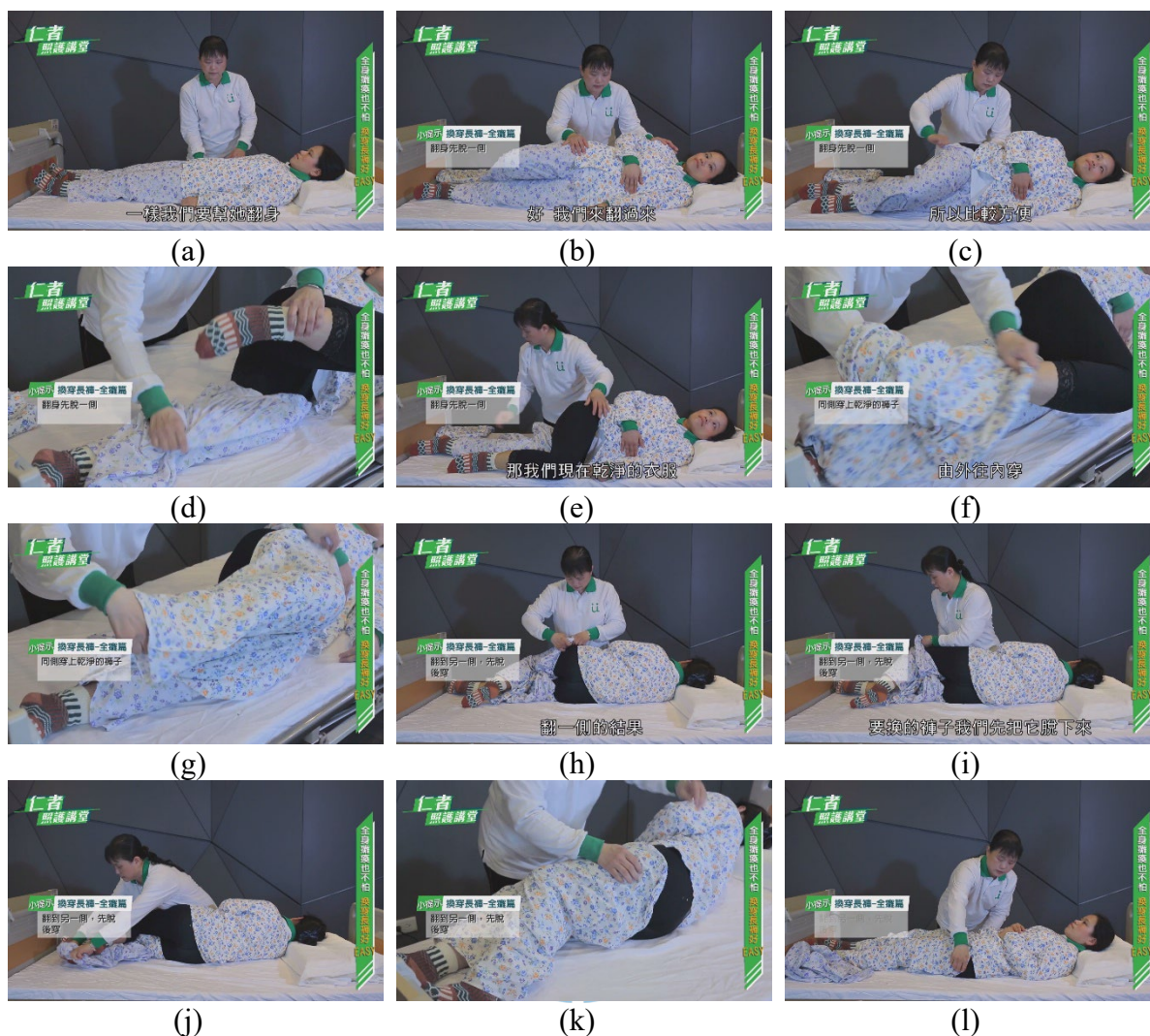


Figure 2-10. Process of conventional changing pants [46].

A T-shirt is the most popular item of clothing among the general population due to its simplicity, but for the bedridden, it is the most difficult to wear. As represented in Figure 2-11, the caregiver is required to elevate the patient's body to create additional space for sliding the T-shirt underneath. This process results in significant discomfort for the bedridden individual during the T-shirt-wearing process, and the direct lifting and physical load of the bedridden is higher. In Figure 2-11, the patient uses a respiratory machine called endotracheal intubation, which is the tube connected to the throat. In this patient's condition, changing the T-shirt using the conventional method is a painful experience [47].

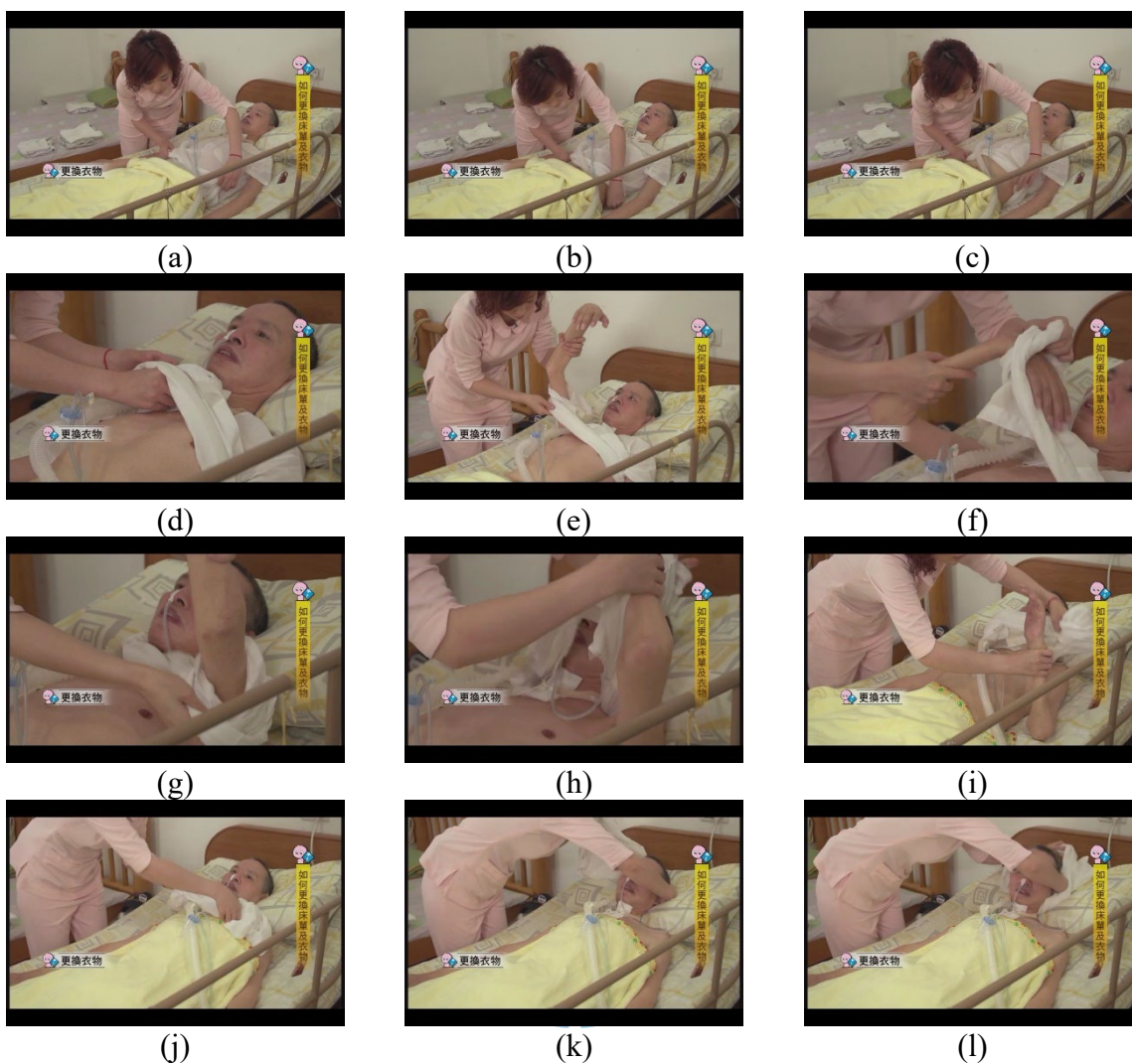


Figure 2-11. Process of conventional T-shirt changes [47].

2.2 Cutting-Edge Insights: Literature Review on Medical Air Mattress

Bed is an essential assistive device for any bedridden patient. There are several functions offered on commercial beds to the bedridden, including bedsore prevention [61], toileting/bedpan change [31, 42], postural change [62], passive limb motion [63], snore reduction [64], and bio measurements(heart rate, respiratory) [65], etc. An ordinary bed used by the bedridden is a medical air mattress (MAM) because it has bedsore prevention as its primary function (Figure 2-12) [66], and the other functions are additional advantages provided by the care provider to cover the needs of the bedridden patient. The regular MAM has some compartments. Despite the fact that it has many compartments, the odd and even matrices inflate alternately [67].

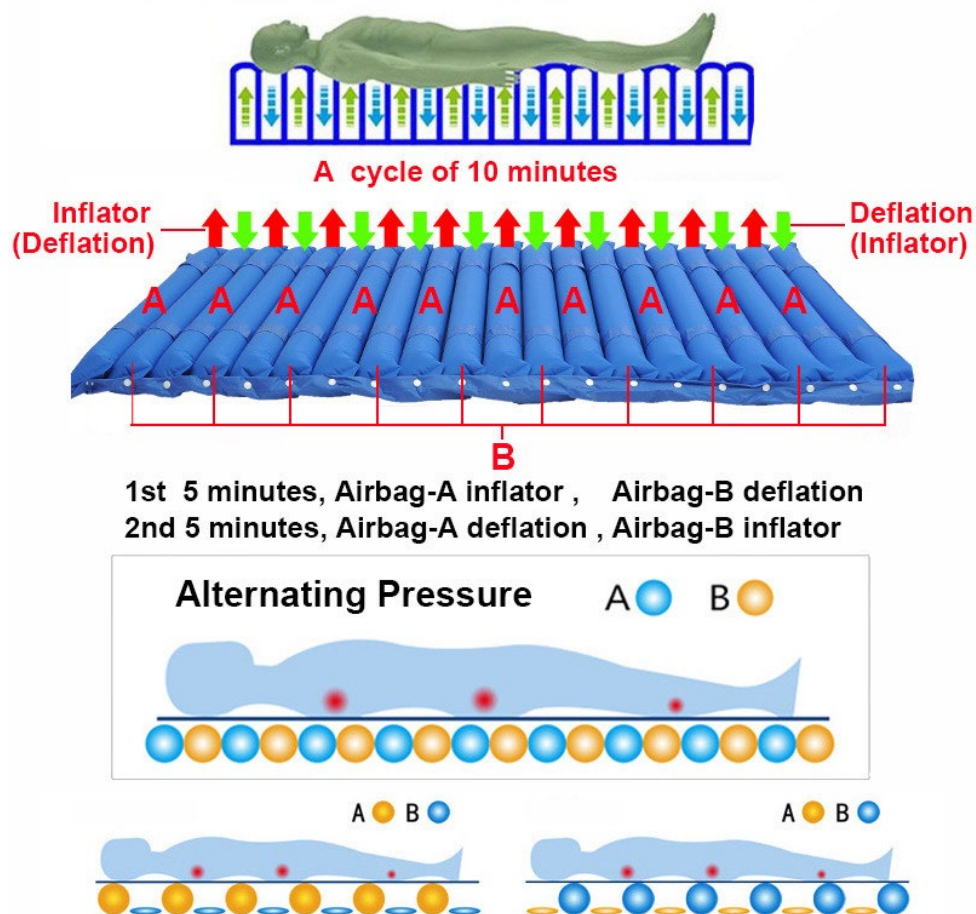


Figure 2-12. Bedsore prevention air mattress [67].

To cover various functions of MAM, including commercial, research, and patent, a third diagram has been made, as shown in Figure 2-13. According to the survey, the main function of the MAM can be divided into two categories: body positioning and bio measurements related to generating movement in the patient's body and the sign of biological signal of the patient, respectively. Most research on MAM focuses on bio measurements, including heartbeat [68, 69], respiration [69-71], snoring [68, 69], sleep apnea [68], body movement [68, 69], coughing [69] and body weigh distribution [72]. Furthermore, the patent and commercial products working on body positioning include bedsores prevention [61], passive limb motion [63], diaper change [42, 73], spinal column correction [74], snore reduction [75], massage [76], toiled/bedpan change [42, 77, 78] and reclining [79].

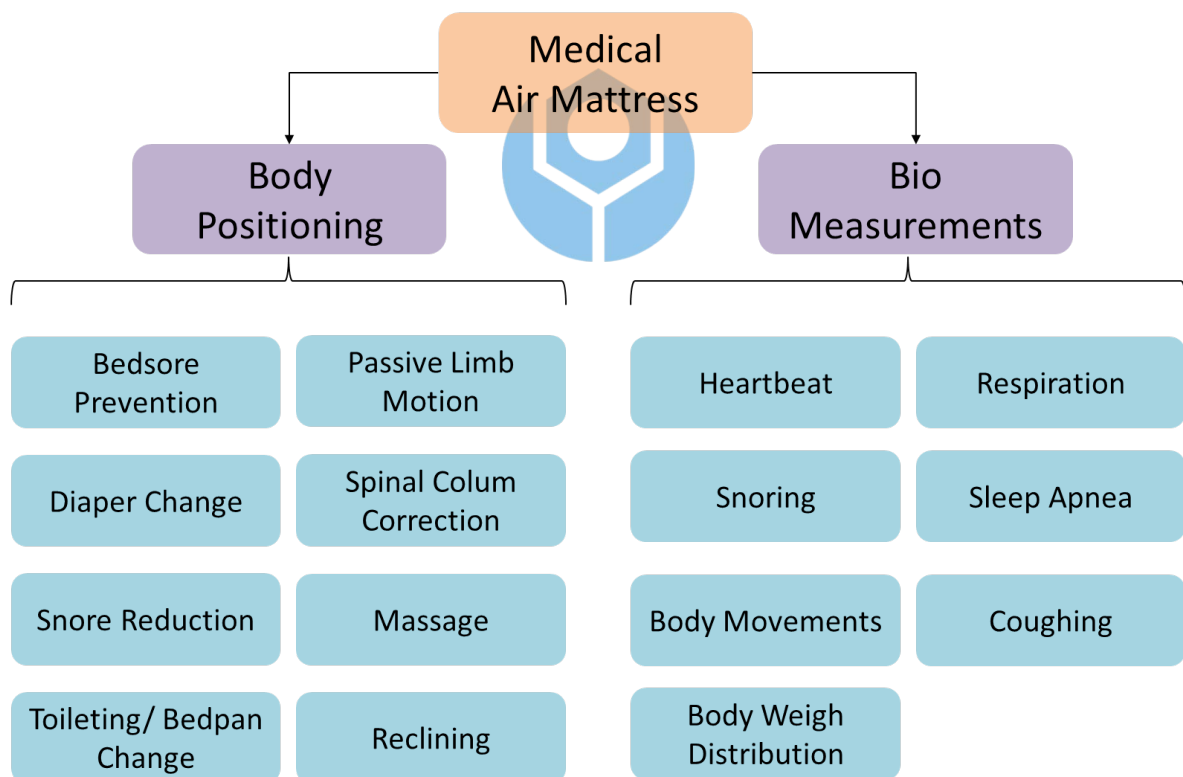


Figure 2-13. Diagram tree of medical air mattress function.

The changing of diapers and bedpans shares commonality in their functions, both involving the management of patient feces or urinary output. In the conventional method, there

are similarities in how patients and caregivers collaborate to facilitate the processes of diaper and bedpan changes. Consequently, certain bed technologies designed to assist with diaper changes may also be adapted for bedpan changes [31]. In addition, bed and mattress technology has many varieties, such as air mattress bedpan compatibility, as shown in Figure 2-14 [77, 78]. However, the diaper and bedpan change on this mattress still requires posture change to replace the diaper or change the bedpan.



Figure 2-14. Air mattress bedpan compatible [77, 78].

Based on the best survey effort, no MAM reference exists, including existing research, patents, and products with clothes change and dry bathing functions. The best source that can be used as a reference to change clothes is an electric bed or mattress, which can change a patient's posture. Many electric beds on the market can change posture from supine to Fowler's position. This approach only works on upper limb patient care, including changing a shirt or t-shirt as represented in Figure 2-15. In Fowler's position, the caregiver must still push the patient's body forward to change the clothes. The Fowler's posture must be at a position of more than 45 degrees in order to facilitate dressing easier [62, 80].

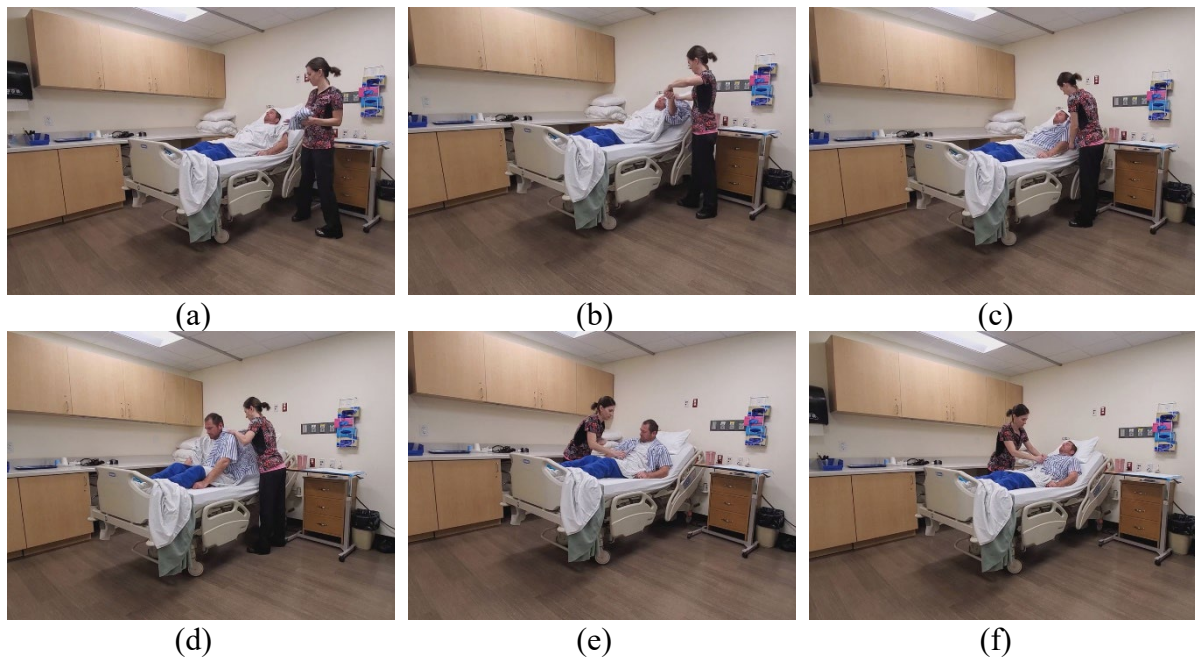


Figure 2-15. Process of changing clothes on the reclining bed [52].

Yuka Omura et al. introduced a back-load reduction mattress for caregivers to turn the patients into lateral positions, as shown in Figure 2-16 [31]. The technique remains the same as the conventional way, with additional machines to support the load of postural change during patient care. The back-load reduction mattress is only valuable for patient care on the lower limb, such as changing pants or diapers. In addition, there is an idea to lift the patient's lower limb by using electric lifter as shown in Figure 2-17. This method looks easy in terms of technique and caregiver load are minimum [59]. However, the method gives stress to patient body due to the lifting supported on the patient's thigh that is awkward and discomfort position for adults.

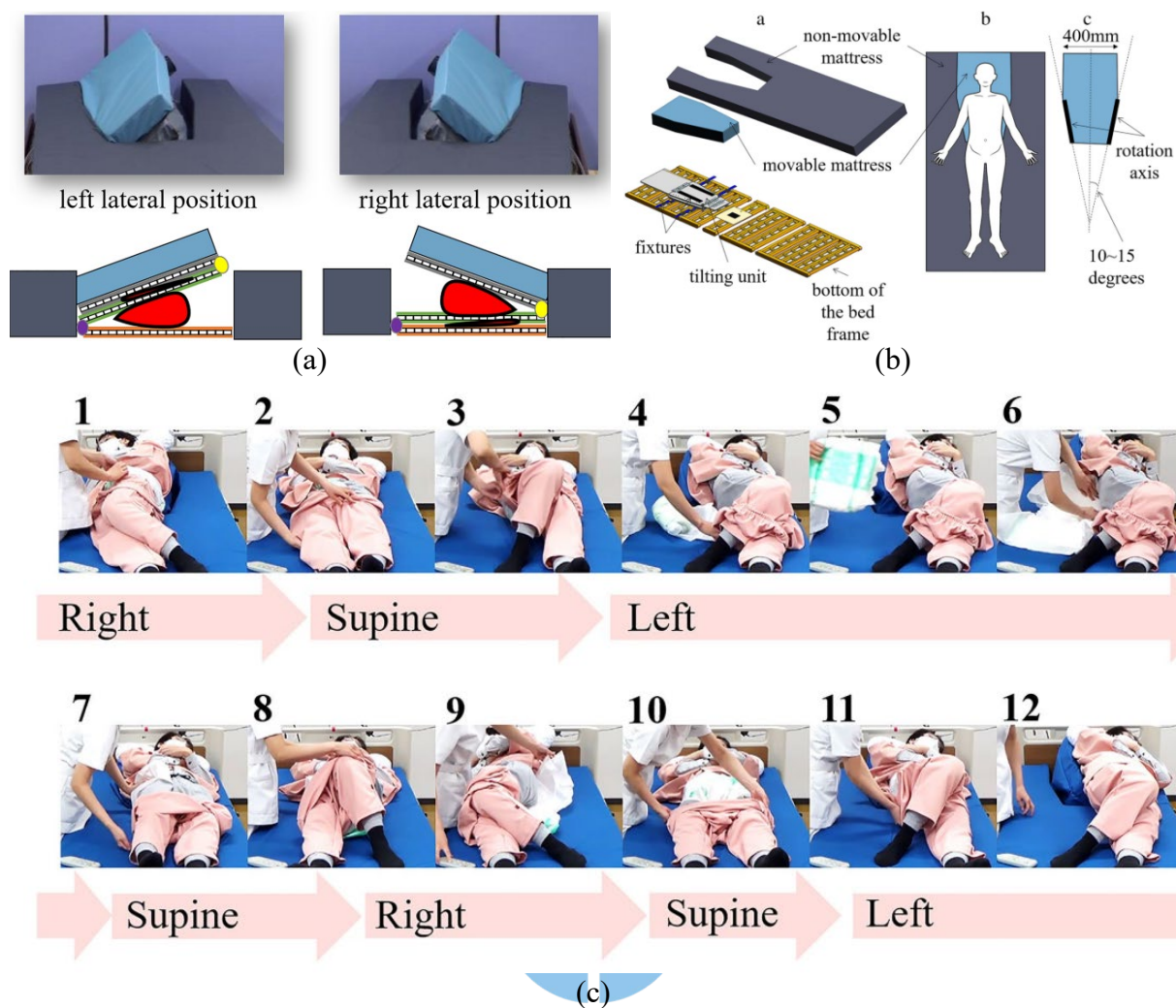


Figure 2-16. Low back load reduction air mattress [31].

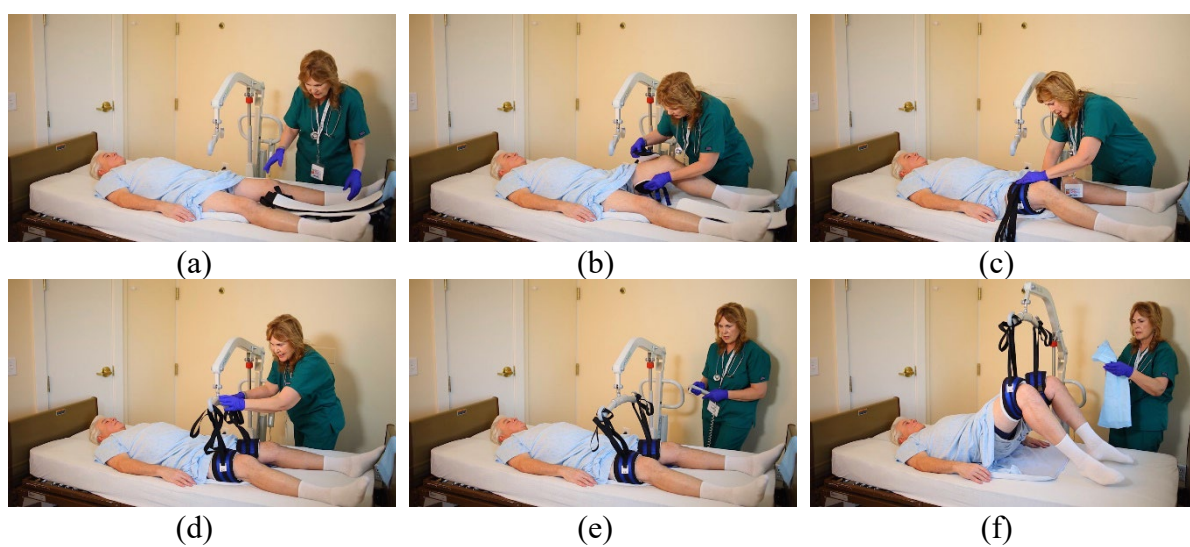


Figure 2-17. Process of diaper replacement or bedpan by using lifter [59].

Although there are already several types of MAM functions, some major gaps for long-term care still exist, including feeding, drinking, bathing, dressing, bladder and bowel management [81]. This research will fill the gap by providing bathing, dressing, bladder and bowel management capability in MAM and improving long-term care quality.

2.3 Electric Controller & Actuator

The Electric Controller and Actuator of an air mattress stand as the central components, serving as the heartbeat of the mechanism. These critical elements form the system of the MAM, enabling the execution of various tasks selected by the user. As the commanding force behind the intricate functionalities of the air mattress, the controller interprets user inputs and precise actions carried out by the actuator. Together, they embody automation that translates user preferences into tangible operations, defining the versatility and adaptability of the air mattress system. This section explains the intricate workings of these components.

2.3.1 Microcontroller

A microcontroller, also known as a microcontroller unit (MCU) or microcontroller (MC), is a miniature computer that is integrated into a single integrated circuit. In addition to memory and programmable input/output peripherals, it may have one or more central processing units (also known as processor cores). On the chip, there is typically a tiny quantity of random-access memory (RAM) in addition to a small amount Read-Only Memory (ROM). In contrast to the microprocessors that are utilized in personal computers and other general-purpose applications that are comprised of a variety of discrete chips, microcontrollers are specifically developed for used in embedded systems with specific functions. They are utilized in the production of products and devices that are operated automatically, such as the control systems of automotive engines, implantable medical devices, remote controls, office machines, appliances, power tools, toys, and other embedded systems. Assembly language was the only

language that was used to program microcontrollers when they were first introduced. However, today, a wide variety of high-level programming languages, including C, Python, and JavaScript, are also being used to target microcontrollers and embedded systems.

The most popular modular microcontroller is Arduino. It is an open hardware design of a single-board microcontroller complete with the standard I/O and software suite for programming, and it also includes the boot loader that runs on the board. The common microcontroller applied to the board is an Atmel AVR processor [82, 83]. In this research, Arduino Mega 2560 was used as the main controller.

2.3.2 Serial Communication

Serial communication transfers a bit of data continuously by the concept of one by another over a communication bus. A serial connection can be made with a few wires compared to parallel communication. Hence, it needs a synchronizing mechanism (clock) as a reference. On the Arduino, there are three types of serial communication such as SPI (Serial Peripheral Interface), I2C (Inter-Integrated Circuit), and UART (Universal Asynchronous Receiver and Transmitter /USART Universal Synchronous and Asynchronous Receiver and Transmitter. There are advantages and drawbacks to each of them. Each of the serial communications is discussed in detail on the following point [84, 85].

A. Serial Peripheral Interface (SPI)

The Serial Peripheral Interface (SPI) is a synchronous serial communication protocol used primarily in embedded systems for short distance wired communication between integrated circuits. It was developed by Motorola in the 1980s and is now a de facto standard used widely in microcontrollers and peripherals. Using a master-slave architecture, Serial Port Interface (SPI) allows for communication to be orchestrated by a single main device. This main device is responsible for providing the clock signal and chip select signal(s), which govern

many subordinate peripherals. Data is transmitted from the master device to the slave device, and the master device likewise receives data from the slave. Due to the fact that it is a full duplex, it is capable of sending and receiving data concurrently. SPI is a sort of serial communication protocol that operates in a synchronous manner. In order to deliver data such as a result, it is composed of six essential line transfers [85].

- MASTER: The main device is used as a clock provider for communication.
- SLAVE: Other devices that utilize the master's clock to communicate.
- MISO: Master In Slave Out, it is a line in which the master sends data to its slaves.
- MOSI: Master Out Slave In, it is a line in which slaves give a response to the master.
- SCK: Serial clock, which is provided by the master device.
- SS: Slave Select is the line used by the master to communicate with the slave.

SPI is commonly used for interfacing microcontrollers with peripheral chips for Secure Digital cards, liquid crystal displays, analog-to-digital and digital-to-analog converters, flash and EEPROM memory, and various communication chips.

In the SPI protocol, there can be only one master but many slave devices. The SPI bus is implemented using 4-signals or wires, and it is sometimes called a Four Wire Interface. The SPI interface can be either 3-wire or 4-wire. The 4-wire SPI interface is the most popular and is used in many applications, including interfacing microcontrollers with various peripheral devices.

B. Inter-Integrated Circuit (I2C)

I2C, which stands for Inter-Integrated Circuit, is a serial communication protocol used for short-distance communication between devices. It was originally designed by Philips Semiconductor in 1982 and is widely used today. I2C uses only two bi-directional open-drain

lines for data communication, called SDA (Serial Data) and SCL (Serial Clock), as shown in Figure 2-18 [86, 87].

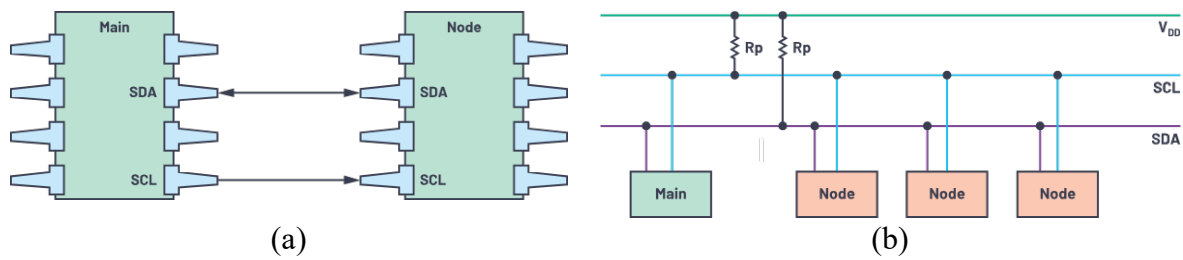


Figure 2-18. Wire diagram of I2C to communicate with each other: (a) Simple communication between two integrated circuits (b) Multiple communication systems [86].

Additionally, the SCL pin is responsible for carrying the clock signal, whereas the SDA pin is responsible for the transfer of data. At the same time that each data bit is being sent on the SDA line, a high-to-low pulse of each clock on the SCL line is synchronizing the data. It is only possible for the data line to change when the clock line is low, as stated by the protocols that govern I2C. The data line cannot change while the clock line is high. Due to the fact that the two lines are open drains, a pull-up resistor is necessary in order to make the lines high. This is because the devices that are connected to the I2C bus are active low [88].

The data is sent via the network in the form of packets, each of which is composed of nine bits. It can generate the sequence of these bits by maintaining the SCL line at a high level and adjusting the level of the SDA line. The sequence is as follows: START and STOP. Altering the SDA from high to low while maintaining the SCL at a high level is what is required to establish the START condition. The STOP condition is generated by increasing the SDA from low to high while maintaining the SCL at a high level [88].

For the purpose of data transmission, I2C makes use of serial transmission. The complexity has decreased since it only makes use of two bi-directional lines, in contrast to SPI communication. As a result of its utilization of the ACK/NACK function, it possesses enhanced

capabilities for handling errors. The I2C communication protocol makes use of some form of communication known as half-duplex. When the Read/Write bit is high, it gives the impression that the master is transmitting the data to the slave. On the other hand, when the Read/Write bit is low, it shows that the master is receiving data from the slave. In comparison to other communication protocols, I2C possesses a number of advantages. The fact that it only makes use of two lines for communication implies that it is easier and less expensive to deploy in comparison to protocols that require a greater number of lines. Because it is also capable of supporting many devices on the same bus, it is an excellent choice for systems that have a large number of low-speed peripherals [88].

C. Universal Asynchronous Receiver and Transmitter (UART)/ Universal Synchronous and Asynchronous Receiver and Transmitter (USART)

UART, which stands for universal asynchronous receiver-transmitter, stands out as one of the widely employed device-to-device communication protocols. This article demonstrates the utilization of UART as a hardware communication protocol through adherence to established procedures. When appropriately set up, UART proves adaptable to various serial protocols, encompassing the transmission and reception of serial data. In serial communication, the transfer of data occurs bit by bit through a single line or wire. For two-way communication, a pair of wires is employed to facilitate successful serial data transfer. The choice of serial communication is influenced by the specific application and system requirements, with the advantage of requiring minimal circuitry and wires, thereby contributing to a more cost-effective implementation. This protocol only uses the Receiver data line (RX) and the Transmitter data line (TX). Without a clock line needed, both devices that communicate should have an internal clock to work at a known baud rate, which helps to sync and fix the data speed of data exchange. Baud rate means data bits transmitted per second, so each device that communicates should maintain a similar baud rate to use this protocol [86, 87].

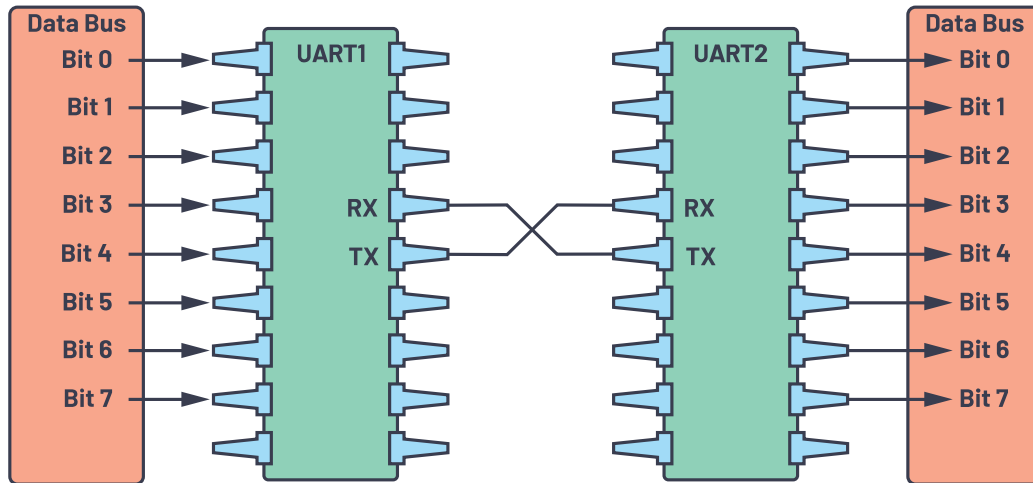


Figure 2-19. UART with data bus [86].

D. CAN BUS

The Controller Area Network, also known as the CAN bus, is a standard automobile bus that was developed to enable microcontrollers and other devices to communicate with one another's applications without the need for a host computer. It is a message-based protocol that was initially developed for multiplex electrical wiring within automobiles in order to reduce the amount of copper that was needed, but it may also be utilized in a wide variety of other settings. The sensors, actuators, and other control devices that are commonly connected via a CAN network are the devices that are connected to the network. The host processor, the CAN controller, and the CAN transceiver are the components that are responsible for connecting these devices to the bus [89].

The transmission of CAN data employs a lossless arbitration method for resolving congestion by individual bit comparison. In order to perform this arbitration procedure, it is necessary for all nodes on the CAN network to coordinate their operations, ensuring that each node samples every bit on the network simultaneously. That is the reason why some refer to CAN as synchronous. Regrettably, the word "synchronous" is inaccurate because the data is transferred in an asynchronous way, namely without a clock signal. CAN protocol is a low-

level protocol that does not include any security measures by default. In addition, standard CAN implementations do not include encryption, which means that these networks are susceptible to frame interception by a man in the middle. For the majority of implementations, it is anticipated that apps would implement their own security procedures. For instance, applications may be expected to authenticate incoming commands or the presence of specific devices on the network. In the event that the adversary is successful in inserting messages on the bus, the failure to establish proper security measures may result in a variety of attacks [89].

The CAN bus is physically organized through a two-wire bus, a twisted pair with a 120 Ω (nominal) characteristic impedance. This bus uses differential wired-AND signals. Two signals, CAN high (CANH) and CAN low (CANL), are either driven to a "dominant" state with $CANH > CANL$ or not driven and pulled by passive resistors to a "recessive" state with $CANH \leq CANL$ as shown in Figure 2-20. When a data bit is set to zero, it indicates a dominant state, and when it is set to one, it indicates a recessive state. This is done in order to accommodate a wired-AND protocol, which provides priority on the bus to nodes with lower ID numbers.

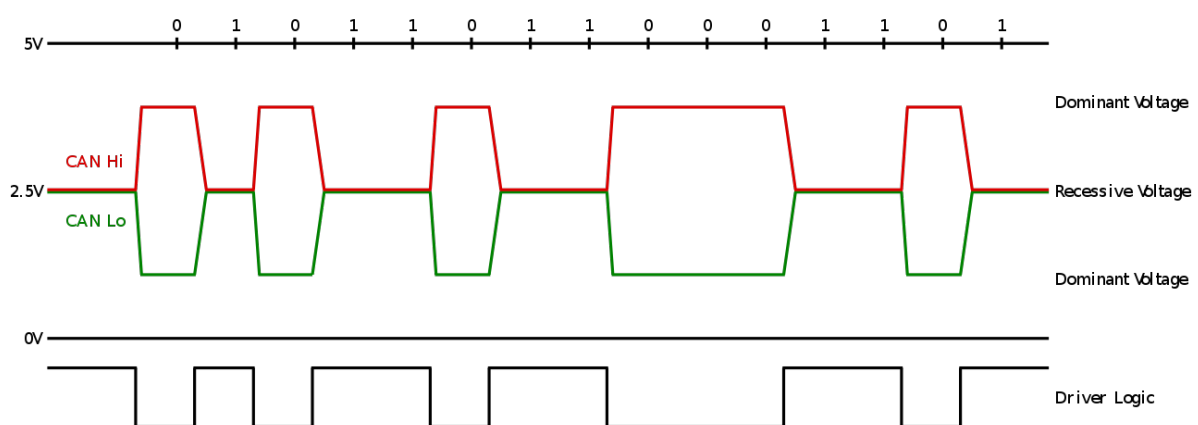


Figure 2-20. Characteristics of CAN bus signal. High-speed CAN signaling. ISO 11898-2 [89].

2.3.3 Pressure Sensors

"Sensor" comes from the Latin word "sentire" which means "to sense". The word sensor was first used during the Middle English period, which lasted from 1350 to 1400. A device that generates outputs that can be processed in response to stimuli, or an input quality is referred to as a sensor. There is a functional connection between these outputs and the stimuli that are being input, which are typically referred to as measurands [90]. As a measurement device, a sensor has several characteristics that need to be considered when getting the proper sensor required for our application. There are characteristics that should be considered:

- | | |
|--------------------------------|--------------------------------|
| 1. Capacity/ Measurement range | 10. Drift |
| 2. Resolution | 11. Minimum Detectable Signal |
| 3. Accuracy | 12. Calibration Curve |
| 4. Precision | 13. Sensitivity |
| 5. Repeatability | 14. Linearity |
| 6. Reproducibility | 15. Selectivity |
| 7. Stability | 16. Hysteresis |
| 8. Error | 17. Response and Recovery Time |
| 9. Noise | 18. Cost-effective. |

Moreover, the selection of a specific sensor also depends on the size, environment, and communication type that is used. For example, a sensor to measure light intensity in the deep sea should be communicated wirelessly to sea level and should be chosen according to those condition-environment requirements.

Pressure is a critical parameter in air mattresses. Each application of MAM has a direct or undirect correlation with the pressure of the chamber. In order to detect a person lying down on the MAM, a pressure sensor module is used, as shown in Figure 2-21.

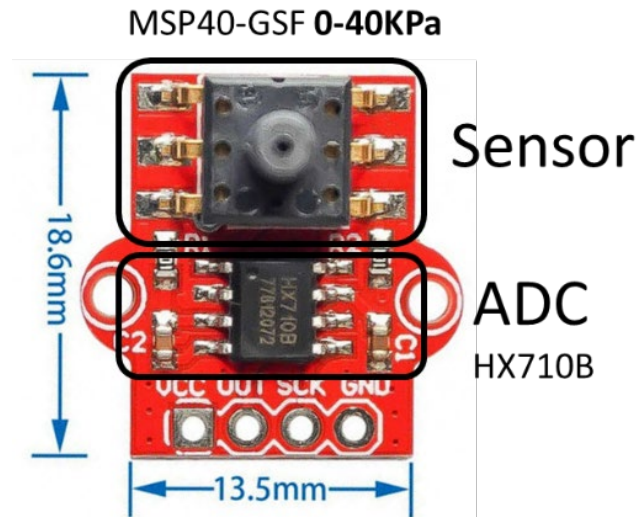


Figure 2-21. Pressure sensor module.

The HX710B functions as a 24-bit Analog-to-Digital Converter (ADC) that emits pulses corresponding to the detected voltage. It operates with a reference voltage range of 1.8 to 5.5V and has a differential input for the Wheatstone bridge configuration, making it suitable for weighing applications. The device also includes a built-in oscillator for generating the clock signal, simplifying the design of the weighing system. The module of pressure sensor application circuit diagrams is represented in Figure 2-22 [91].

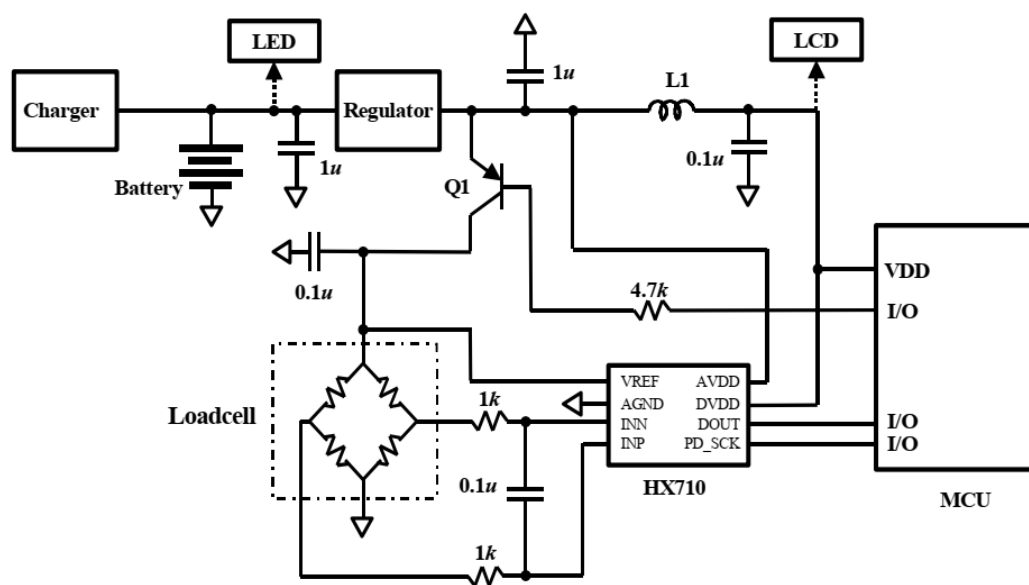


Figure 2-22. Typical Wheatstone bridge application block diagram [91].

The pressure sensor employs the MSP40-GSF, which has a rated pressure range of 0-40Kpa. It has features of a Wheatstone bridge configuration, as illustrated in Figure 2-23. The pressure sensor has linear characteristics with respect to voltage along the rated pressure, as shown in Figure 2-24. In accordance with the attributes of the pressure sensor in Figure 2-24, a conversion process is employed to translate voltage readings into corresponding pressure values as described in equation (1)-(4).

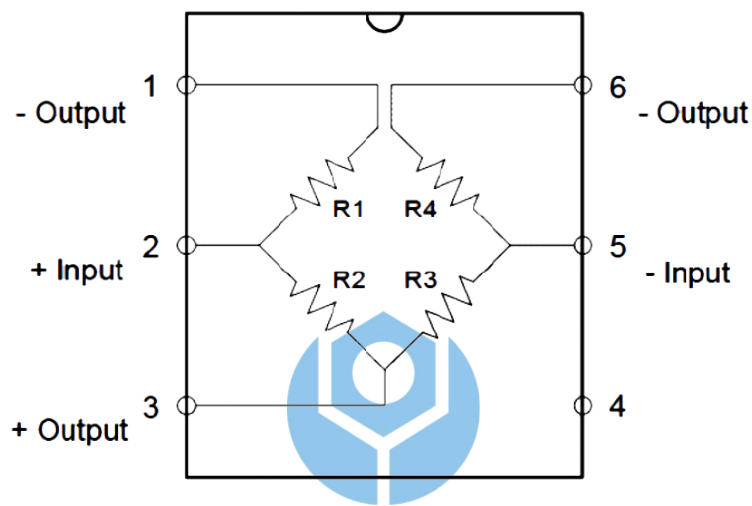


Figure 2-23. The configuration of the pressure sensor MSP40-GSF [91].

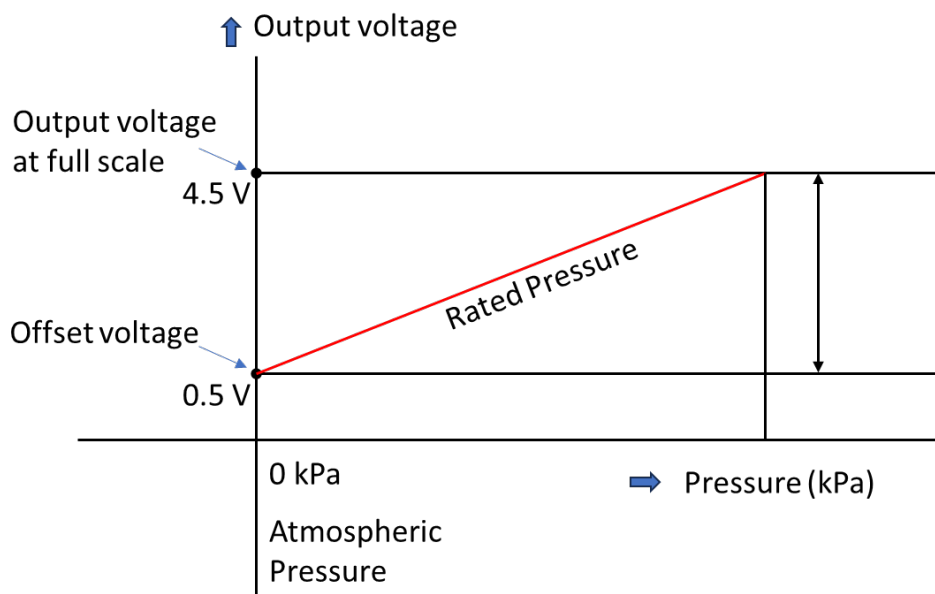


Figure 2-24. Electric characteristics of a pressure sensor [91].

$$\frac{V-V_1}{V_2-V_1} = \frac{P-P_1}{P_2-P_1}, \quad (1)$$

$$P = \left(\frac{V-V_1}{V_2-V_1} (P_2 - P_1) \right) + P_1, \quad (2)$$

V_1 and V_2 are offset voltage and output voltage at full scale respectively. While the V is actual reading of the pressure sensor. P_1 , P_2 and P are lowest, highest rated pressure and actual pressure respectively [91]. The actual voltage can be defined from the equation below.

$$ADC \text{ value} = \frac{V}{\text{Sensitivity}}, \quad (3)$$

$$V = ADC \text{ value} \cdot \text{Sensitivity}, \quad (4)$$

From the characteristics of pressure sensor and the described equation, an algorithm to operate the pressure sensor is developed as shown in Figure 2-25.

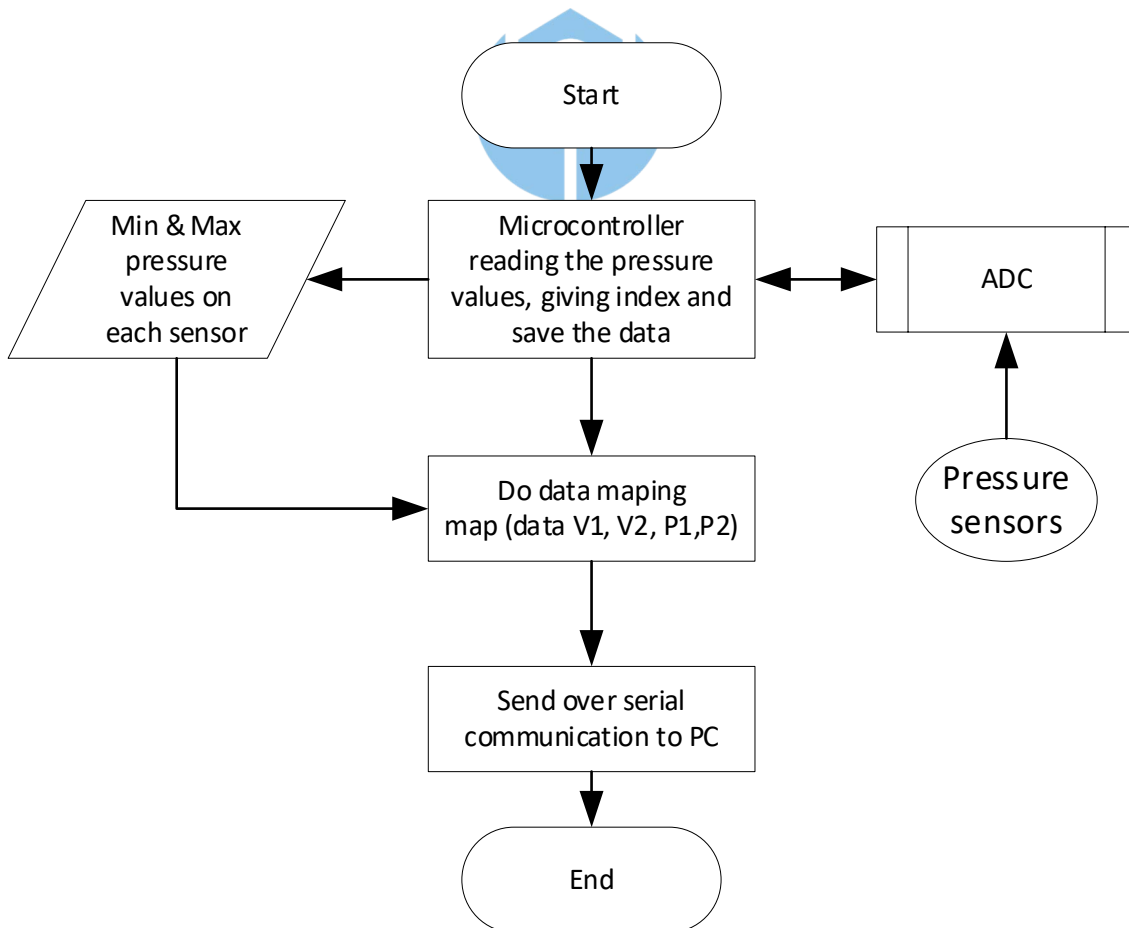


Figure 2-25. Pressure sensor reading and mapping.

2.3.4 GPIO Expander

A GPIO (General Purpose Input/Output) expander is a device that provides additional GPIO pins for a microcontroller or other digital system. This is particularly useful when the number of available GPIO pins on a microcontroller is insufficient for a particular application [92]. GPIO expanders can provide from 4 to 128 GPIO pins, depending on the specific model of the expander. For example, the PCA9555 is a 24-pin CMOS device that provides 16 bits of General-Purpose parallel Input/Output (GPIO) expansion for I²C-bus/SMBus applications, as shown in Figure 2-26 [93]. The NXP Semiconductors line of I²C-bus I/O expanders needed to be improved therefore this was built to do just that. The enhancements consist of a greater drive capability, a tolerance of 5 V I/O, a lower supply current, individual I/O configuration, and smaller packaging [93].



Registers for input, output, and polarity inversion (active HIGH or active LOW operation) are included in the PCA9555. Additionally, there are two 8-bit configuration registers that allow for the selection of either input or output. This is accomplished by writing to the I/O configuration bits, which allows the system controller to enable the I/Os to function as either inputs or outputs. The information that pertains to each input or output is stored in the register that corresponds to that input or output. Through the use of the Polarity Inversion Register, it is possible to transform the polarity of the read register. It is possible for the system controller to read all of the registers [93]. When any input state is different from the state of its associated input port register, the open-drain interrupt output of the PCA9555 is active. This output is intended to notify the system controller that an input state has changed. During the power-on reset, the registers are automatically reset to their default values, and the device state machine is initialized [93].

The I2C-bus address can be changed using three hardware pins (A0, A1, and A2), which also make it possible for up to eight devices to use the same I2C-bus or SMBus. Because the fixed I2C-bus address of the PCA9555 is identical to that of the PCA9554, it is feasible for up to eight of these devices, in any combination, to share the same I2C-bus/SMBus. This makes it possible to control up to 128 GPIO pins on an Arduino by utilizing only two lines. It provides a versatile set of general purpose inputs and outputs (GPIOs), and the wide VDD range of 1.65-5.5 volts enables the PCA9555A to interface with microprocessors and microcontrollers of the next generation, which are experiencing a decrease in supply levels in order to promote power conservation [93].

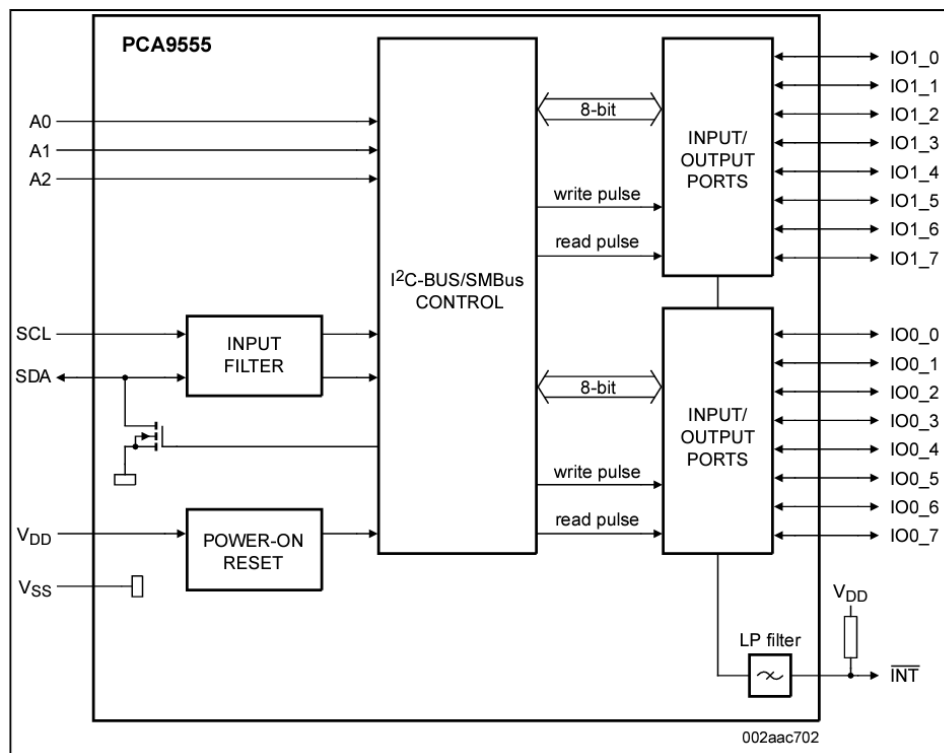


Figure 2-26. PCA9555PW block diagram [93].

2.3.5 Electronic Driver (DC Switching)

Direct Current (DC) power switching refers to the process of controlling the flow of DC through an electronic circuit using a switch. This is a common requirement in many

electronic devices, such as computers, mobile phones, and automotive systems, where power needs to be controlled to manage energy consumption, protect circuits, and manage system states. There are several types of DC power switching techniques, including [94]:

- 1) Load switches are electronic switches that turn power rails on and off. When the internal FET turns on, current flows from the input to the output and passes power to the downstream circuitry. When the device is enabled, the rise time of the output voltage (VOUT) can be controlled by adjusting the capacitance on an external pin. When the device is disabled, the fall time of VOUT is controlled through the quick output discharge (QOD). QOD pulls the output to the ground whenever the device is turned off, preventing the output from floating or entering an undetermined state.
- 2) Power MUX devices are similar to load switches but allow for multiple input sources. This set of electronic switches is used to select and transition between two or more input power paths to a single output while also providing input power protection.
- 3) E-Fuses and HotSwap controllers provide additional input power path protection functions such as current sense monitoring, current limiting, undervoltage and overvoltage protection, and thermal shutdown. This makes these devices ideal for hot-plug and transient events that would otherwise damage system components.
- 4) Ideal Diode, ORing Controllers: Ideal diode, ORing controllers offer protection against reverse-polarity circumstances by monitoring an external FET, leading to a large reduction in power loss and preventing reverse current from flowing. The controller will monitor and make adjustments to the external FET whenever a transient event takes place in order to prevent any harm to components that are located upstream.
- 5) Off-board load protection is the purpose of smart high-side switches, which are also known as smart high-side switches. Additional diagnostic telemetry is provided by them, which monitors the output load current and detects situations such as open-load and short-

circuiting. Smart high-side switches have current restrictions that can be adjusted, which enables them to be integrated into applications that have either high inrush current startup profiles or low peak currents in a more dependable manner.

- 6) Low-side switches are similar to high-side switches in that they link the load to the ground rather than providing a connection between the load and the power supply. Low-side switches enable the elimination of inductive load transients through the dissipation of current in a circular loop. This is accomplished through the use of an integrated flyback diode. They are able to operate inductive loads like solenoids, relays, and motors as a result of their capabilities.

Each of these switching techniques has its own advantages and is suited to different applications. The choice of which to use depends on the specific requirements of the electronic device or system being designed. A simple example of DC switching to control a solenoid valve is represented in Figure 2-27 [82].

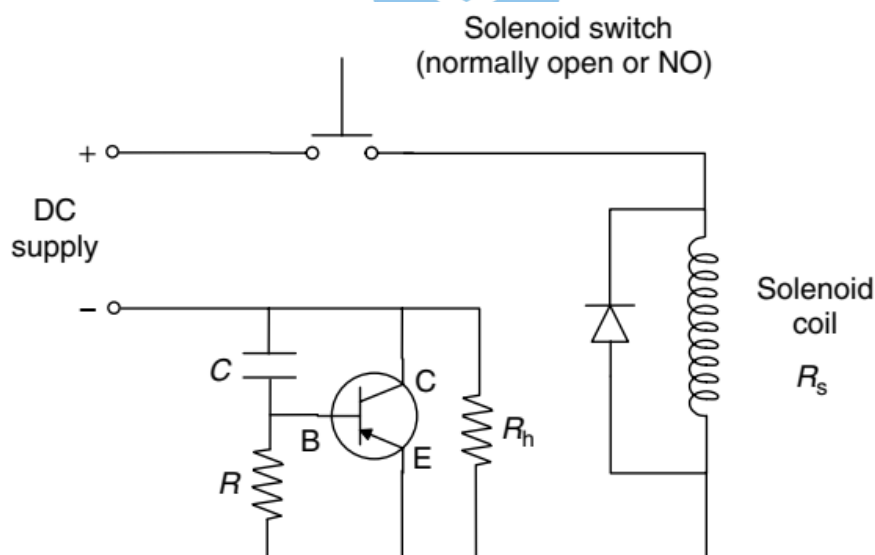


Figure 2-27. Transistor as DC driver [82].

Some DC switching use electro-mechanical principle such as solenoid. A tightly coiled wire that generates a magnetic field when electricity flows through it is known as a solenoid

coil as shown in Figure 2-28 [82]. This type of wire can be utilized to move things, generate power, or activate a solenoid actuator [95]. A solenoid can be turned on by powering voltage across its terminals and turned off by powering it off. To control this, turn the process on and off using a digital circuit, and a switching device like MOSFET or Transistor is used as shown in Figure 2-27. The solenoid used for switching is called relay as represented in Figure 2-28. Relay is designed to convert the logic voltage from the controller input supply to a higher workload including higher voltage or current. A diode is connected in the opposite direction of the parallel direction in order to prevent the solenoid coil from discharging into the power circuit [96].

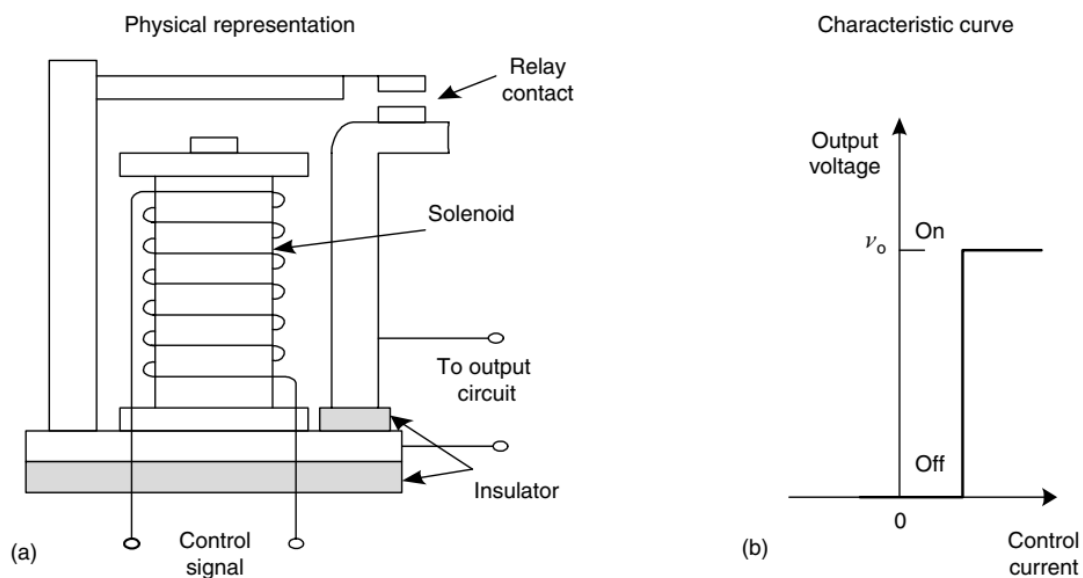


Figure 2-28. Solenoid diagram: (a) Physical representation of the solenoid on the relay application (b) Characteristic of the solenoid when the current flows over the coiled wire [96].

3.2.1 Solenoid Valve

A solenoid valve is a valve driven by a solenoid actuator. Its inner core is a magnetic field generator that is powered by a wire coil. Many different types of locking, industrial, automotive, and medical devices use this magnetic field to move an armature [95]. The

solenoid has several designs according to its function. The common model of the solenoid valve is a two-way model that is represented in Figure 2-29 [97].

The basic principle of a solenoid valve is a force balance of the magnetic force of the solenoid on one side, the pressure of the medium, and the force of the spring on the other side. This force balance is used to control flow. Solenoid valves are used in a variety of applications [95]:

- 1) Uses for locking mechanisms include applying a magnetic field to a solenoid, which moves a plunger to secure the device in place. Once the power is out, a spring will release the lock by pushing the plunger back. Doors, vending machines, access barriers, and countless other types of security systems.
- 2) Solenoids have several uses in automobiles, including gear shifters, engine starters, fuel injection systems, door locks, valve actuators, and fuel injection systems.
- 3) Controlling fluid flow, regulating valves in medical gas systems, operating pumps and dispensers, and controlling the movement of medical equipment are all examples of medical applications that make use of solenoids.
- 4) Solenoid applications in railroading include fuel injection and exhaust gas recirculation in diesel engines, as well as the operation of switches and signals, brake control, door and window actuators, and other similar tasks.
- 5) Valve control, pneumatic and hydraulic system operation, clutch and brake actuators, equipment movement control, automation, robotics, and manufacturing are just a few of the many industrial applications.

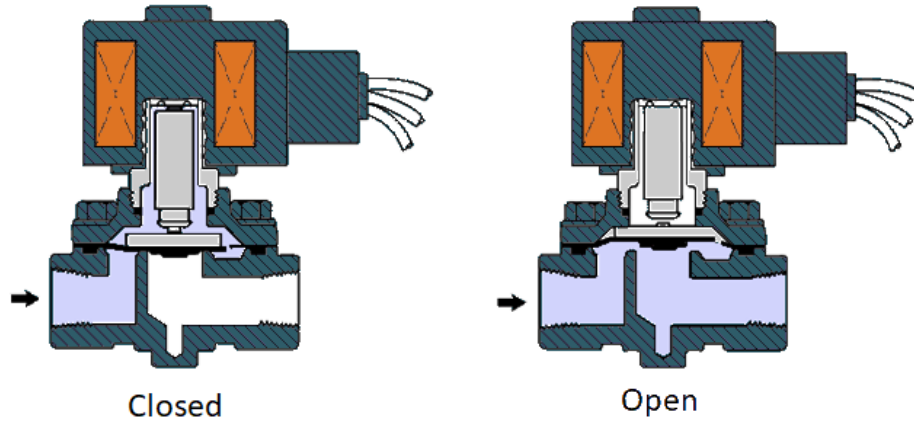


Figure 2-29. A two-way model of a solenoid valve [97].

3.2.2 Centrifugal Compressor

In the context of the medical air mattress, a compressor is employed to generate pressure within the chambers, inflating them to a predetermined level. Two compressor models are currently utilized in the existing MAM: the reciprocating displacement and centrifugal compressor. The reciprocating compressor is widely preferred for its low-speed alternation and reduced noise levels and is commonly applied in MAMs prioritizing these features. On the other hand, the centrifugal compressor is predominantly used in standard air mattresses, performing one-time inflation with higher noise levels. However, it boasts the advantage of a high flow rate and is capable of rapidly inflating the entire air mattress within seconds.

In our specific application, which necessitates a natural speed of inflation in each chamber or cell, a high-flow-rate compressor becomes imperative, a feature uniquely provided by the centrifugal compressor. There exists a pressure limit imposed on delivering air to the chamber, dictated by considerations of patient comfort and material constraints. Excessive pressure can result in an uncomfortably rigid chamber, akin to lying on a hard surface, with the added risk of a chamber explosion. Conversely, insufficient pressure may cause the patient's

body to conform unevenly to the air mattress, following the distribution of weight. Achieving an optimal balance is crucial to ensuring both patient comfort and the safety of the air mattress.

In a centrifugal compressor, the air or gas enters axially into the impeller and discharges radially. Most compressors in industrial applications use electric motors to drive them. This process increases the speed of the working fluid (gas or air) by converting the kinetic energy into speed. However, the diffuser further converts the speed of the air or gas into pressure energy, as represented in Figure 2-30 [98, 99]. Radial centrifugal compressors possess a significant advantage over axial compressors due to their higher-pressure ratio at low flow rates. A centrifugal compressor involves the compression of a specific vapor or gas with the assistance of the compressor impeller. If highly compressed gas is desired, these compressors can be arranged in multiple stages. Elevating the pressure of the compressed gas can be achieved by increasing the number of compressor stages. To meet varying pressure requirements for different functions, multiple stages can be connected in series to achieve the desired pressure [88].

The operating principle of a centrifugal compressor differs slightly from that of a reciprocating compressor. During the startup process, air is introduced into the centrifugal compressor from either the air tank or another suitable source. The air strikes the impeller subsequent to its entry into the compressor. Multiple radial blades comprise this impeller, which rotate in tandem with the impeller itself. When air encounters the radial blades of the impeller, it is compelled to move towards the center of the impeller due to centrifugal force. The impeller blades impart kinetic energy to the air upon impact, resulting in an increase in its velocity. Upon traversing the impeller, the air proceeds to enter the diffuser region. The vans of this diffuser are stationary. As soon as the air enters the diffuser region, its velocity or speed begins to decrease. The relationship between pressure and velocity squared is inversely

proportional, as stated in Bernoulli's principle. Before the air is drawn into the impeller center, the increased velocity of the air is converted to pressure energy by the diffuser or casing of the volute. Under the majority of circumstances, the rise in diffuser pressure will be approximately equivalent to the increase in impeller pressure. There are two varieties of centrifugal compressors: single-stage and multi-stage [88].

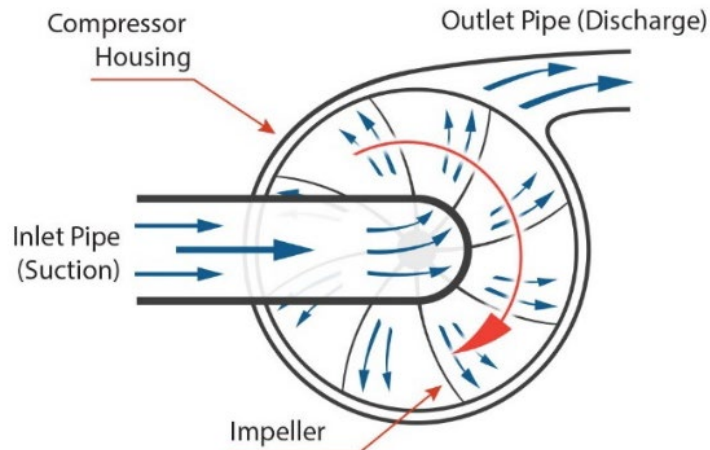


Figure 2-30. Centrifugal compressor illustration [88].

3.2.3 Electric Motor

In the realm of air mattress technology, the compressor's operational dynamics are facilitated by an electric motor. Specifically, in the design of the proposed Multichambered MAM, an alternating current (AC) motor is incorporated, a prevalent selection for driving centrifugal compressors. Electric motors, pivotal components in this context, are categorized into two primary types based on their power source: direct current (DC) motors and AC motors, as shown in Figure 2-31 [100]. The discerning choice for the proposed MAM is the utilization of an AC motor, a decision motivated by its widespread applicability in driving centrifugal compressors [100].

The electric motor is composed of a stationary part called the stator and a moving part called the rotor, as shown in Figure 2-32. The clearance between the stator and the rotor is required to provide space for the rotor to spin, and the distance gap can vary depending on the

motor models. The stator and rotor generate a magnetic field that continuously develops torque to function as a motor driving a mechanical load [100].

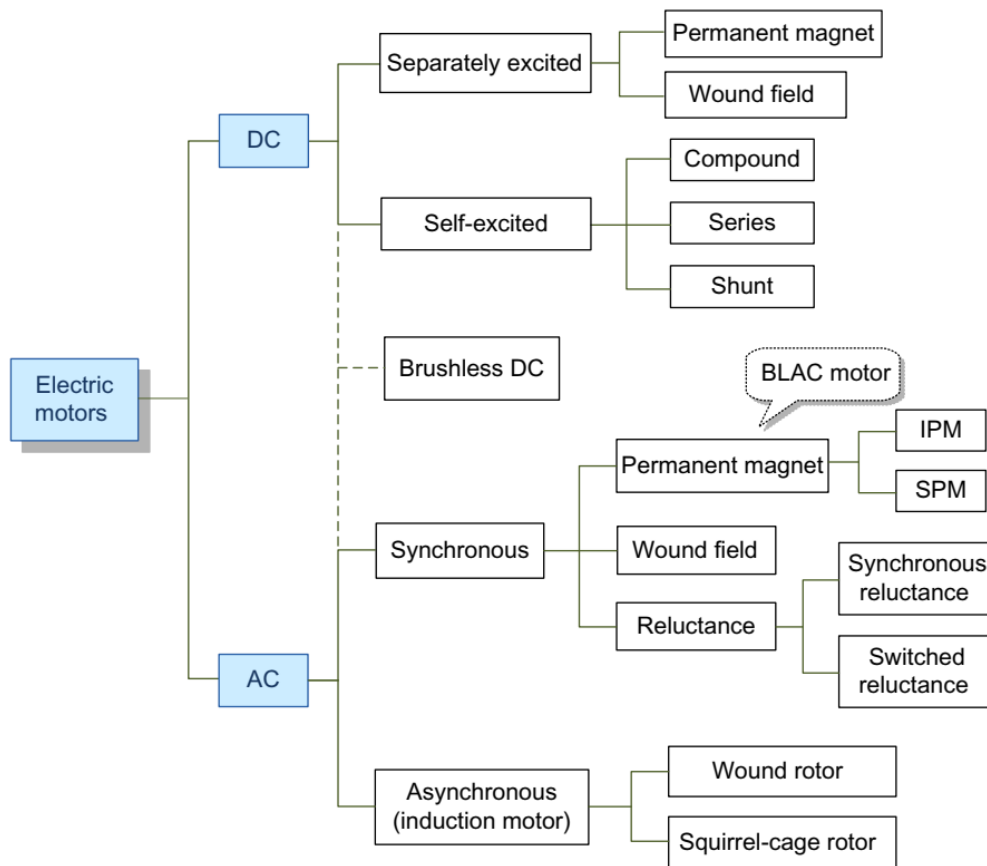


Figure 2-31. Classification of electric motors [100].

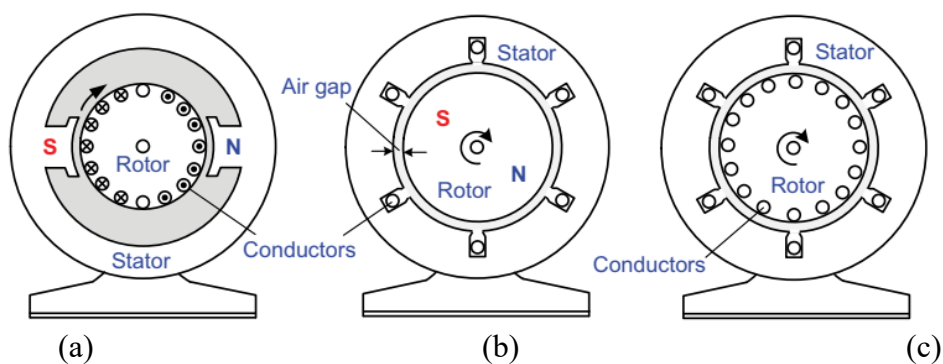


Figure 2-32. Configuration of electric motors. (a) DC motor, (b) AC synchronous motor, and (c) AC induction motor [100].

Torque production of a motor can be evaluated from how the force (or torque) is being produced inside by applying the law of conservation of energy: "within an isolated system, energy can be converted from one kind to another or transferred from one place to another, but it can neither be created nor destroyed". The application of the law of conservation of energy when the electromechanical energy conversion device acts as a motor is shown in Figure 2-33 [100].

The electric energy dW_e is a source for the energy conversion device during the differential time interval dt and is converted into magnetic field energy dW_f and mechanical energy dW_m . Therefore, the total amount of energy is constant [100].

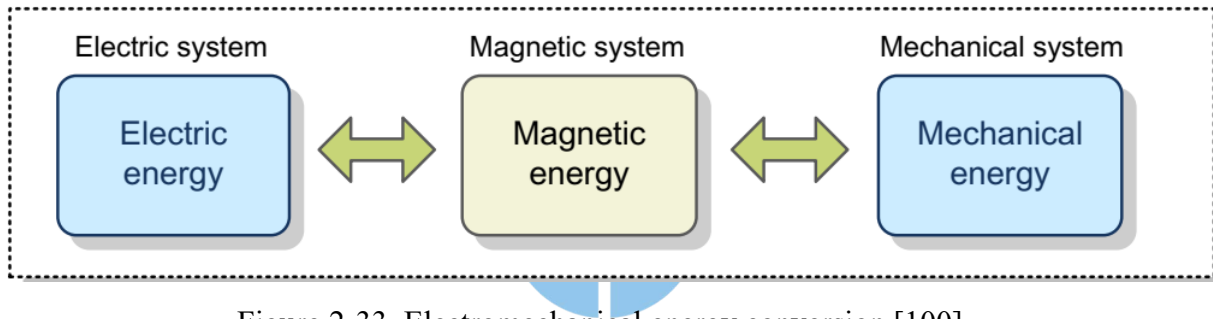


Figure 2-33. Electromechanical energy conversion [100].

Moreover, the conversion of energy practically always has losses. In the electrical motor, there are several losses, including copper losses in an electric system, core losses such as hysteresis and eddy current losses in a magnetic system, and mechanical losses such as friction and windage losses. The energy losses are dissipated as heat and noise. For evaluating energy conversion, the losses can be neglected. Therefore, the conversion energy of the electric motor equation can be written as equation (5) [100].

$$dW_e = dW_f + dW_m \quad (5)$$

CHAPTER 3

PROPOSED METHOD AND PROTOTYPING

3.1 System Overview

The initial model of the programmable multichambered Medical Air Mattress (MAM) system showcases a one-dimensional layout extending along the longitudinal direction of the mattress, depicted in Figure 3-1. This prototype comprises 20 individual chambers, each featuring a pair of solenoid valves connected to negative and positive pressure pumps. An important characteristic of this design is the ability to independently adjust the air pressure in each chamber, allowing for precise customization based on specific needs.

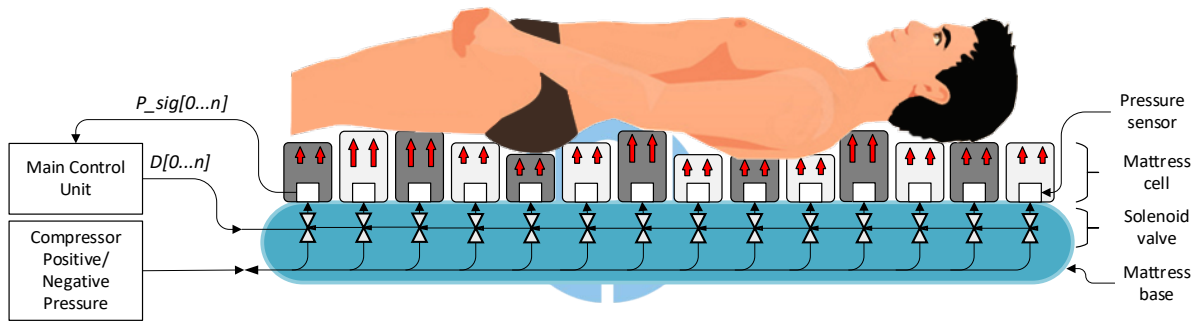


Figure 3-1. The design concept of the 1D Medical Air Mattress.

The programmable MAM system's second model features a two-dimensional layout extending both longitudinally and transversally across the mattress, illustrated in Figure 3-2. This concept comprises 79 individual chambers, each equipped with a pair of solenoid valves linked to negative and positive pressure pumps. The distinctive feature of this design lies in its capacity to independently adjust the air pressure in each chamber, allowing for precise customization and optimization based on specific requirements. A cell with a red number indicates a position that is inactive or is not used for any ADL. The early stages of this multichambered MAM prototype is to study the mechanical design and controller.

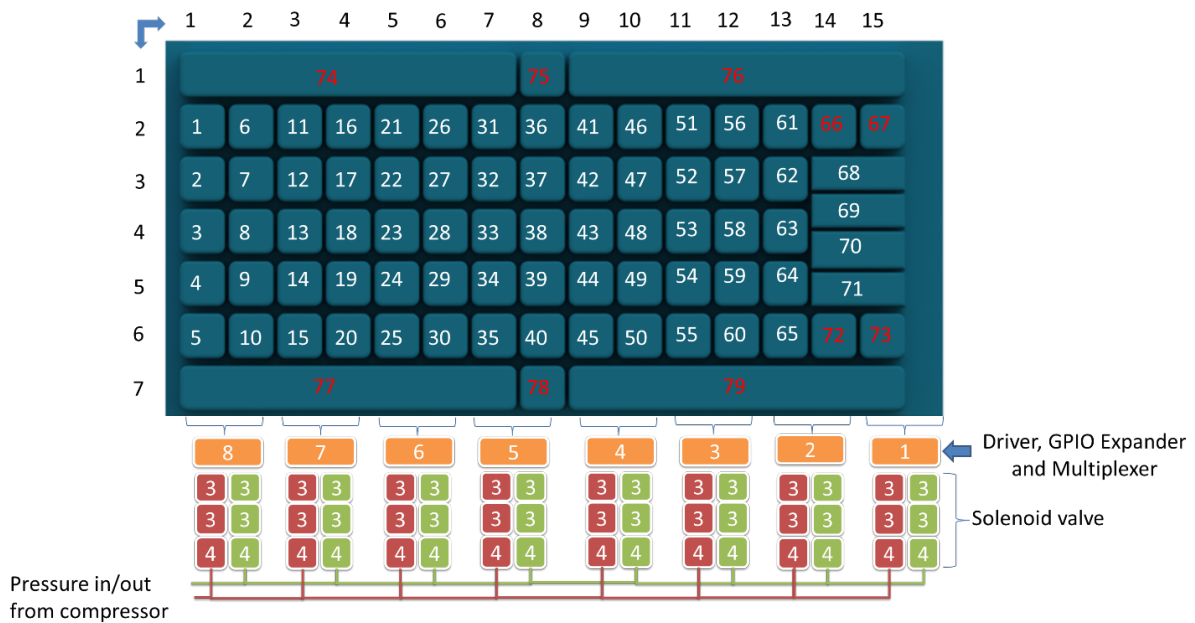


Figure 3-2. The design concept of the 2D Medical Air Mattress.

Furthermore, the second prototype have several concepts to improve the function of bedpan and diaper replacement with denser cell as represented in Figure 3-3. The denser cell in the middle can help the patient with a different body size and accurately give support while performing ADL.

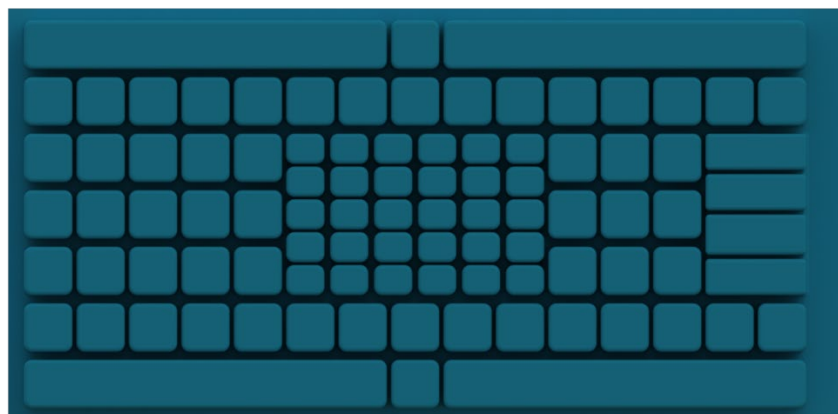


Figure 3-3. Denser cell in the middle to improve the function of MAM.

To send commands to the mattress, a graphical user interface (GUI) is made as depicted in Figure 3-4. It contains a com port, a mattress task, and a camera display. The chamber number is not the same as the concept and the prototype due to the code was optimized up to

80 cells which may be needed in the future development. This basic GUI is still under development to show pressure data on the MAM.

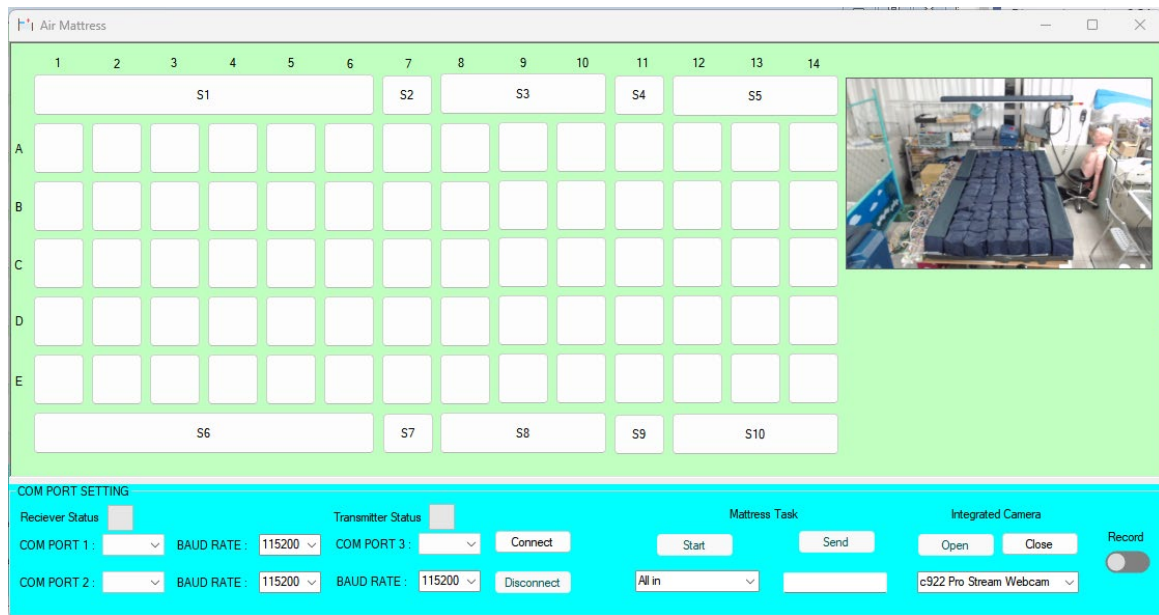


Figure 3-4. Graphic user interface of MAM to send commands and receive feedback.

3.2 Electronics and Controller

The design of the controller is represented in Figure 3-5. This prototype uses an AT-Mega 2560 as the main controller. All the logic devices work on a 5-volt level. The GPIO expander PCA9666APW is used to tackle the limitation of the I/O of the microcontroller. An I2C communication protocol is applied between the microcontroller and GPIO Expander. GPIO expander is connected to transistor BD 139 to drive the solenoid valve. Its transistor is used to amplify the voltages from 5 volts to 12 volts. Based on this design plan, the controller module PCB was fabricated, as shown in Figure 3-6.

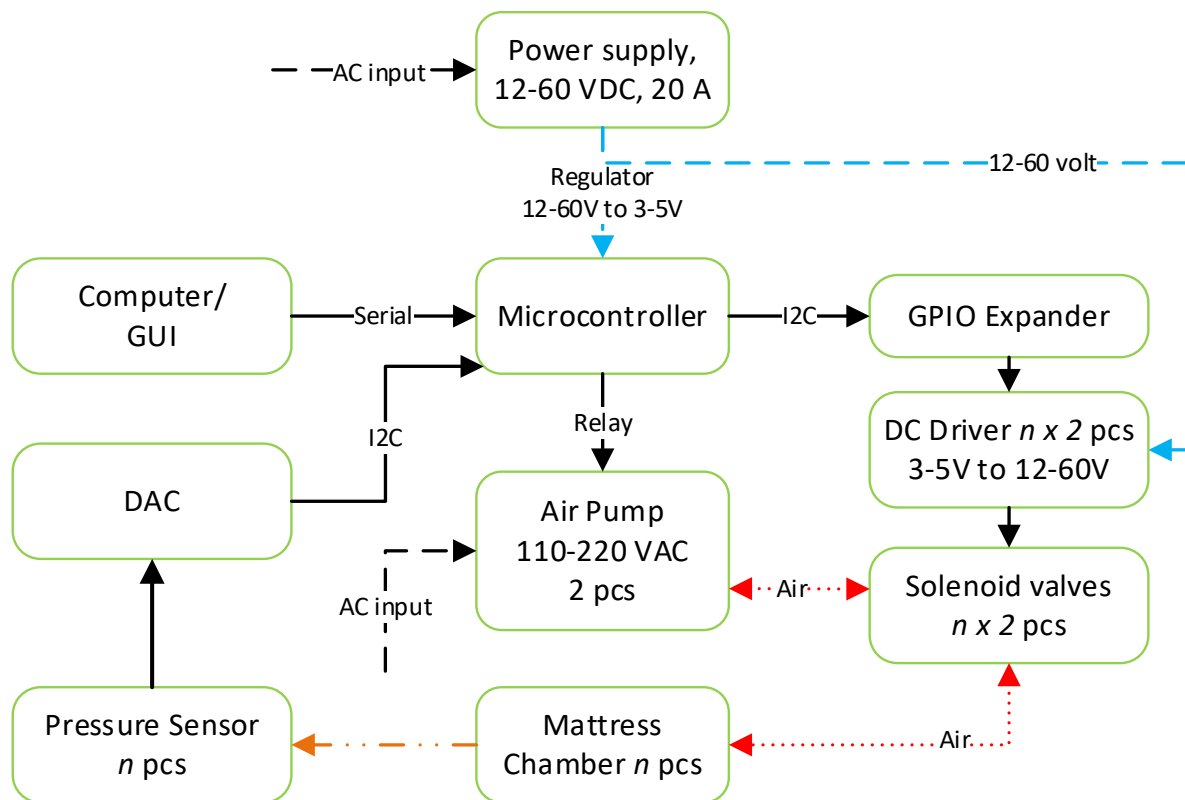


Figure 3-5. Electronic diagram of the air mattress.

A pair of AC motor pumps generate positive and negative pressures. The positive and negative pressure tubes are connected to the head and suction of the pumps, respectively. These pumps are driven by relays, which are controlled by the microcontroller. These pumps are independent and can be turned on or off according to the required pressure. The pumps can deliver air up to 660 L/min, with an electrical specification of 110-120 volt at 250 watts, which can create a pressure of up to 1.2 PSI. The tasks can be selected from the computer, and the signal can be sent to the microcontroller by the serial communication protocol.

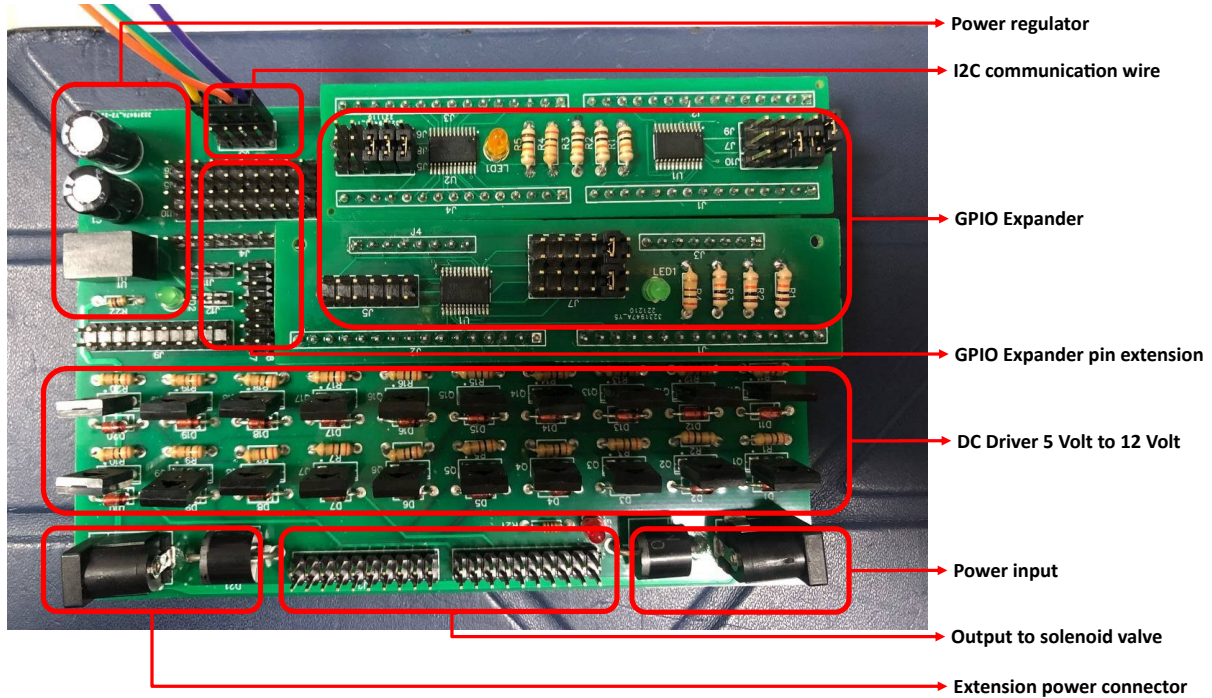


Figure 3-6. Electronic development boards.

3.3 Air Mattress Prototype

The first prototype is a one-dimensional medical air mattress, which is represented in Figure 3-7. The left side of the MAM is a controller and solenoid valve arrangement. In the middle are air mattress chambers. The chamber is made of TPU material and has a diameter and length of + 74mm and + 810mm, respectively. The total dimension of MAM is 81 x 180 cm. Other parts, including the pump and power supply, are located beneath the bed. The controller and tubing use the setup for second prototype which has capability to drive 80 chambers. Therefore, the first prototype is only connected to 20 tubes, then the algorithm needs to be changed to perform any experiments in 20 chambers.

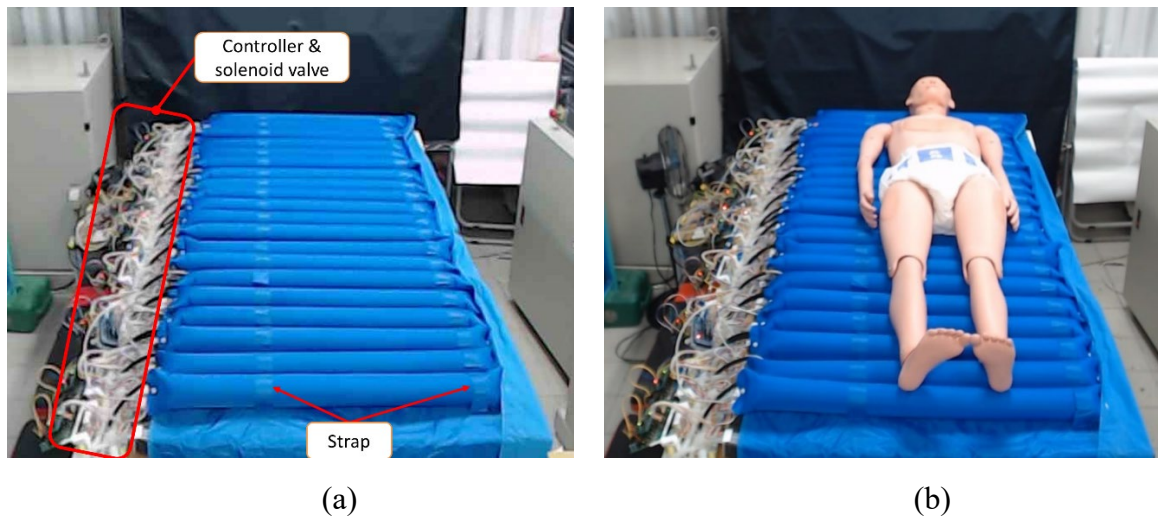


Figure 3-7. One-dimensional MAM prototype: (a) Mechanical and electrical configuration
(b) Experimental setup and a medical mannequin.

The significance of the second prototype lies in its incorporation of multiple cells, thereby reducing chamber size to accommodate Activities of Daily Living (ADL) tasks that necessitate a more confined space for efficient management. Particularly noteworthy is the attention given to addressing the needs of bedridden individuals facing incontinence challenges. The design focuses on enhancing the feasibility and effectiveness of crucial ADL tasks, specifically bedpan and diaper changes, for individuals with limited mobility and incontinence concerns. By optimizing the chamber size, this prototype acknowledges the importance of creating a space-efficient and dignified bedpan and diaper change procedures, contributing to the overall well-being and comfort of bedridden individuals grappling with incontinence-related issues. The second prototype of MAM is represented in Figure 3-8. Numbers 1 and 2 represent an upper and lower section of the solenoid group to manage the controller address easily, respectively. The total dimension is the same as the one-dimensional mattress. There is a different cell size on the top side which supports the head of patient. Since this area is not crucial for the experiment, the dimension of the cell was changed during prototyping. There are three different shapes which are the dimensions of 120x120x150, 840x120x150, and

240x120x150 cm² with total of 76 cell. Additionally, Figure 3-9 shows the mattress to support each individual cell. The tube-nozzle connections to the cell are under the surface base.

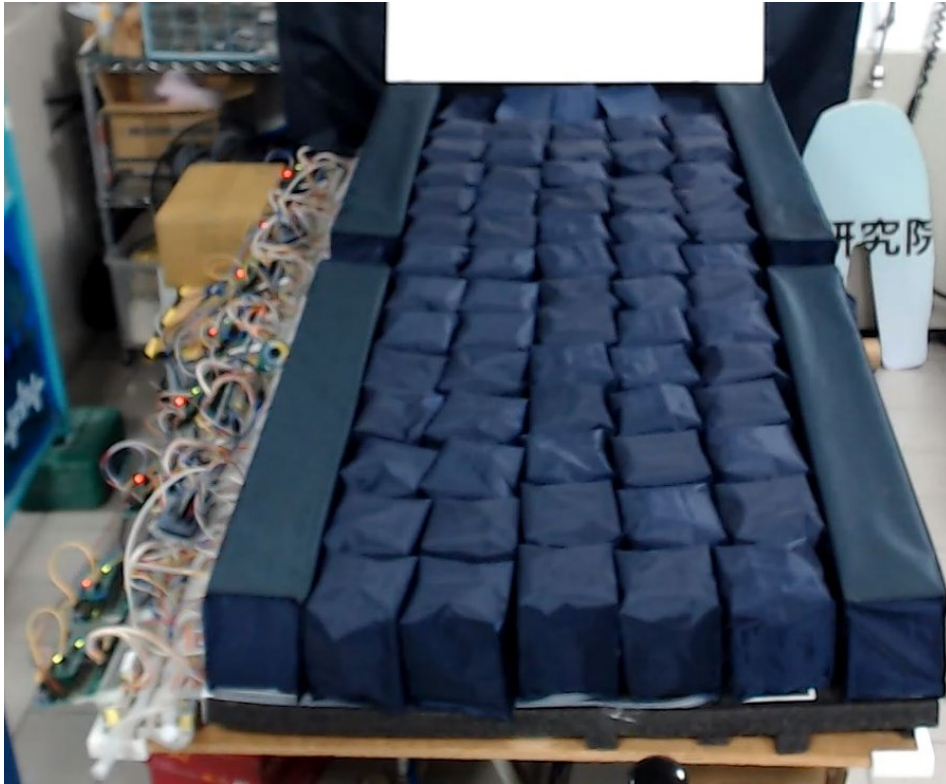


Figure 3-8. Two-dimensional MAM prototype.



Figure 3-9. Base of two-dimensional of MAM prototype.

Tubing is one of the important parts of this prototype which delivers pressurized air and vacuum. The tubing configuration is depicted in Figure 3-10. The tube includes a main tube and distribution tube which have sizes of 8 and 4 mm, respectively. The pump configuration to create pressurized air and vacuum is shown in Figure 3-11.

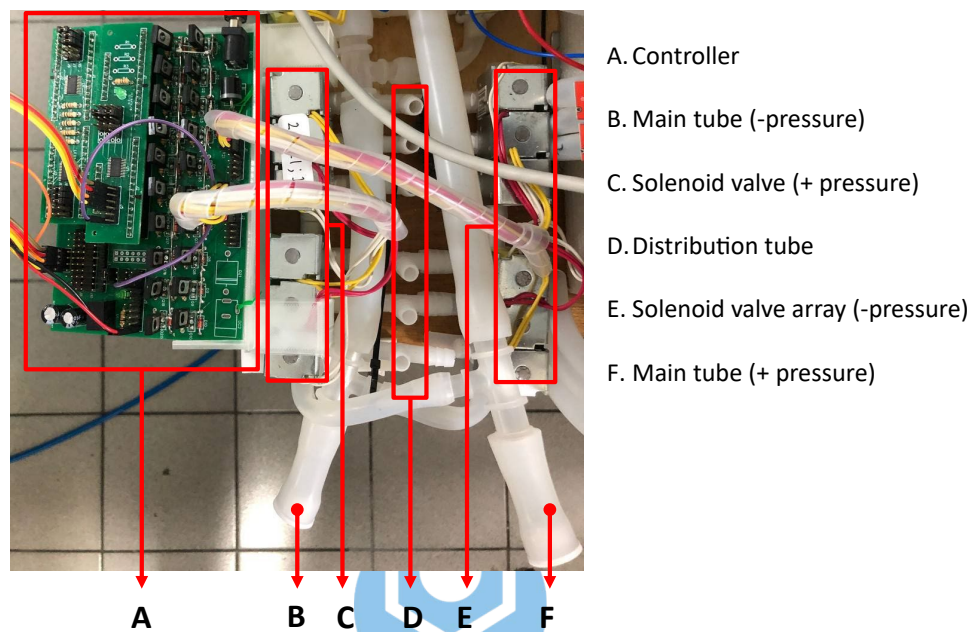


Figure 3-10. Tubing and solenoid configuration.

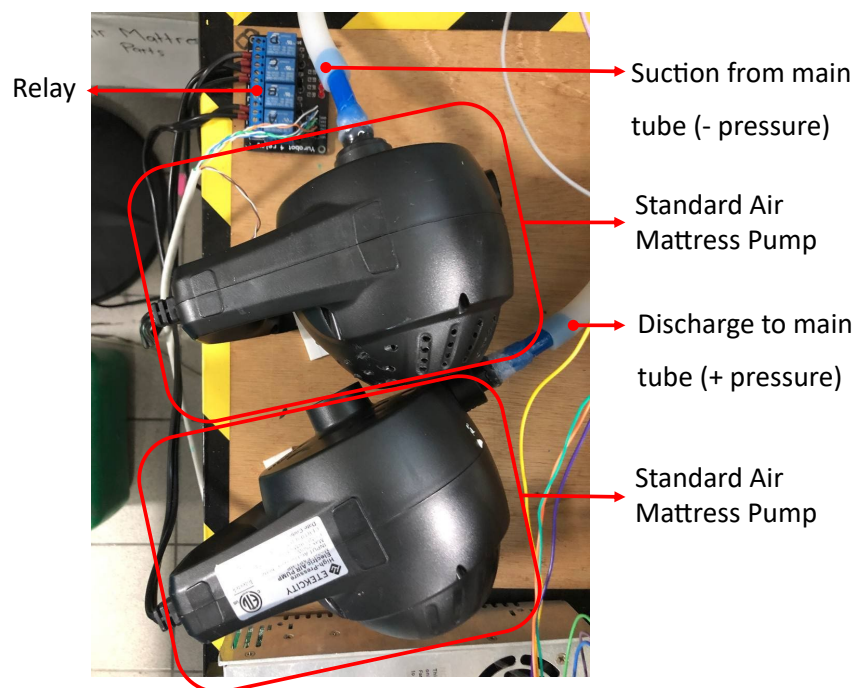


Figure 3-11. Pump configuration.

3.4 Methodology

Figure 3-12 demonstrates a simple task of MAM, which only requires a one-dimensional model, such as bathing and changing clothes. Other tasks may require the two-dimensional model, such as bedpan and diaper change, as shown in Figure 3-13. The red marks in Figure 3-13 represent the active chamber, which may inflate or deflate according to the desired task.

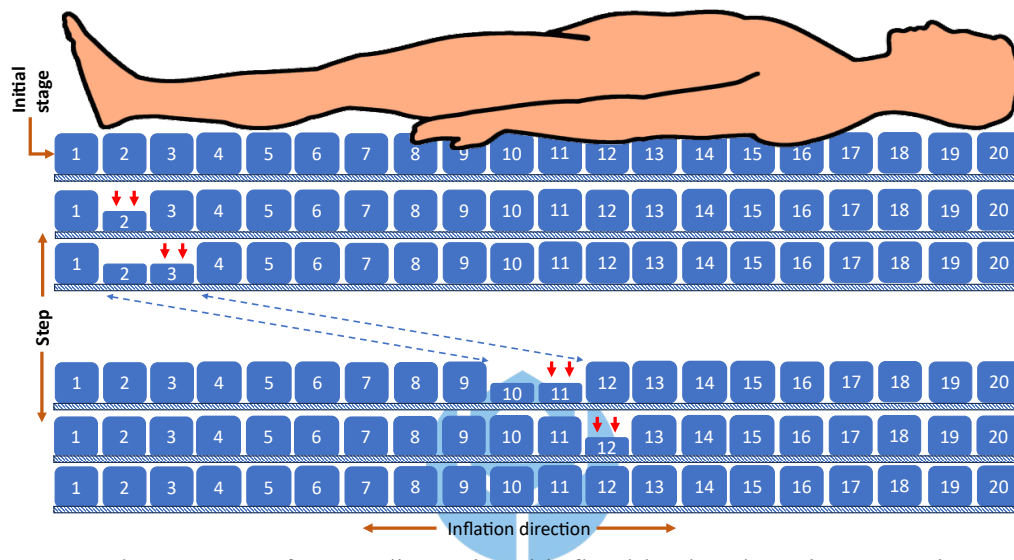


Figure 3-12. The concept of a one-dimensional inflatable chamber gives caregivers space to perform activities beneath the patient's body, such as bathing and changing clothes.

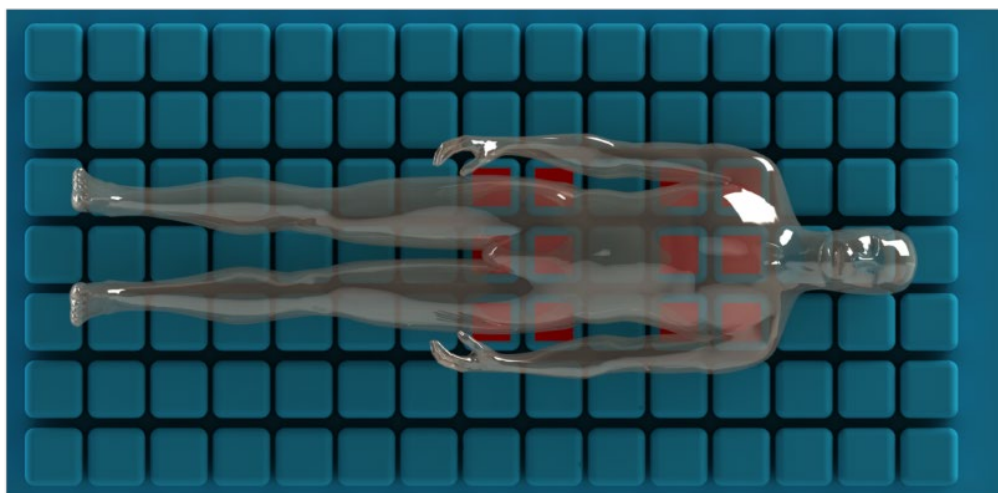


Figure 3-13. The concept of a two-dimensional inflatable chamber gives caregivers space to perform an activity beneath the patient's body.

3.5 Conceptual Framework for Active Daily Living on a Medical Air Mattress

This section explores the technical complexities of implementing ADL using the suggested MAM framework. The technical concept states that a mattress with only one dimension is designed to carry out specified functions, as explained in the thorough concept description. However, some activities of daily living require the sophisticated functionalities of a two-dimensional mobile assistive machine. The ADL activities presented in this conceptual framework include a range of crucial caregiving duties, such as bathing, bedpan changes, diaper changes, and clothes changes. This section highlights the flexibility and capabilities of the proposed MAM to meet the many needs of caregivers assisting those with limited mobility by explaining the technological details.

3.5.1 Bathing

The innovative bathing concept introduced for the proposed MAM revolves around the strategic provision of ample space beneath the patient's body. This thoughtful design allows caregivers just enough room to effectively and comfortably clean the body surrounding the deflated chamber. The extent of deflation in the chamber is adaptable and contingent upon the specific positioning of the patient on the mattress, as visually depicted in Figure 3-14 a-d. As an additional step in the bathing procedure, attention is directed towards hair cleaning. In this proposed method, a further deflation of the chamber is implemented, specifically in the head area. This intentional deflation allows for the accommodation of a water container, which serves the dual purpose of collecting residual water during the hair cleaning process, enhancing the overall efficiency of the procedure, as shown in Figure 3-14 e.

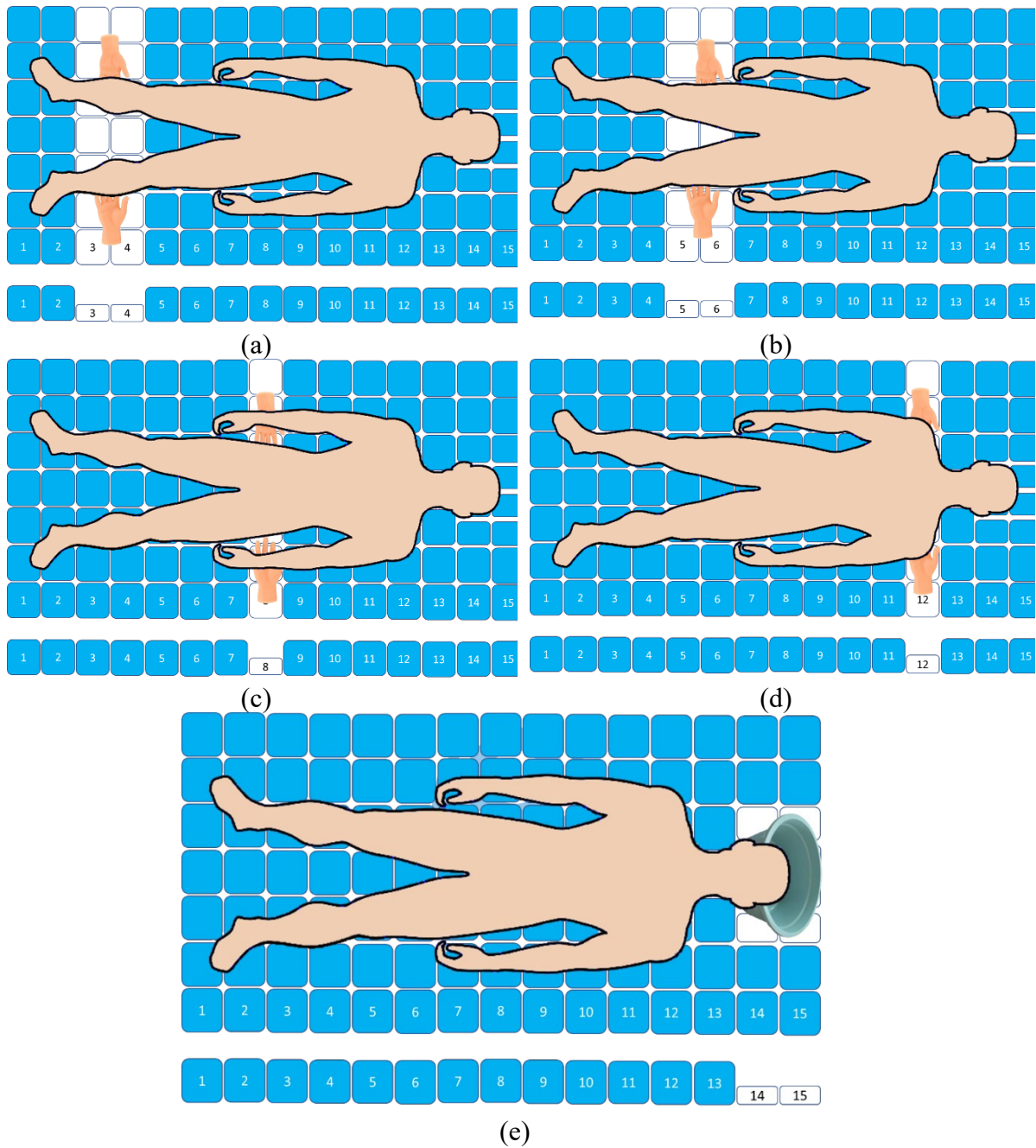


Figure 3-14. Concept of bathing sequence.

3.5.2 Changing a Diaper

The implementation can involve putting on or taking off pants, which would activate the MAM along the middle of the patient's body around the buttock. The technique for changing diapers involves two fundamental methods: support and space. As illustrated in Figure 1, achieving balance for a rigid body requires a minimum of three supporting points.

These points encompass the left and right areas between the buttocks and thighs, as well as along the lower back or hip. Adequate space is also necessary to facilitate diaper changing beneath the genital area, allowing for easy cleaning on both the left and right sides of the buttocks.

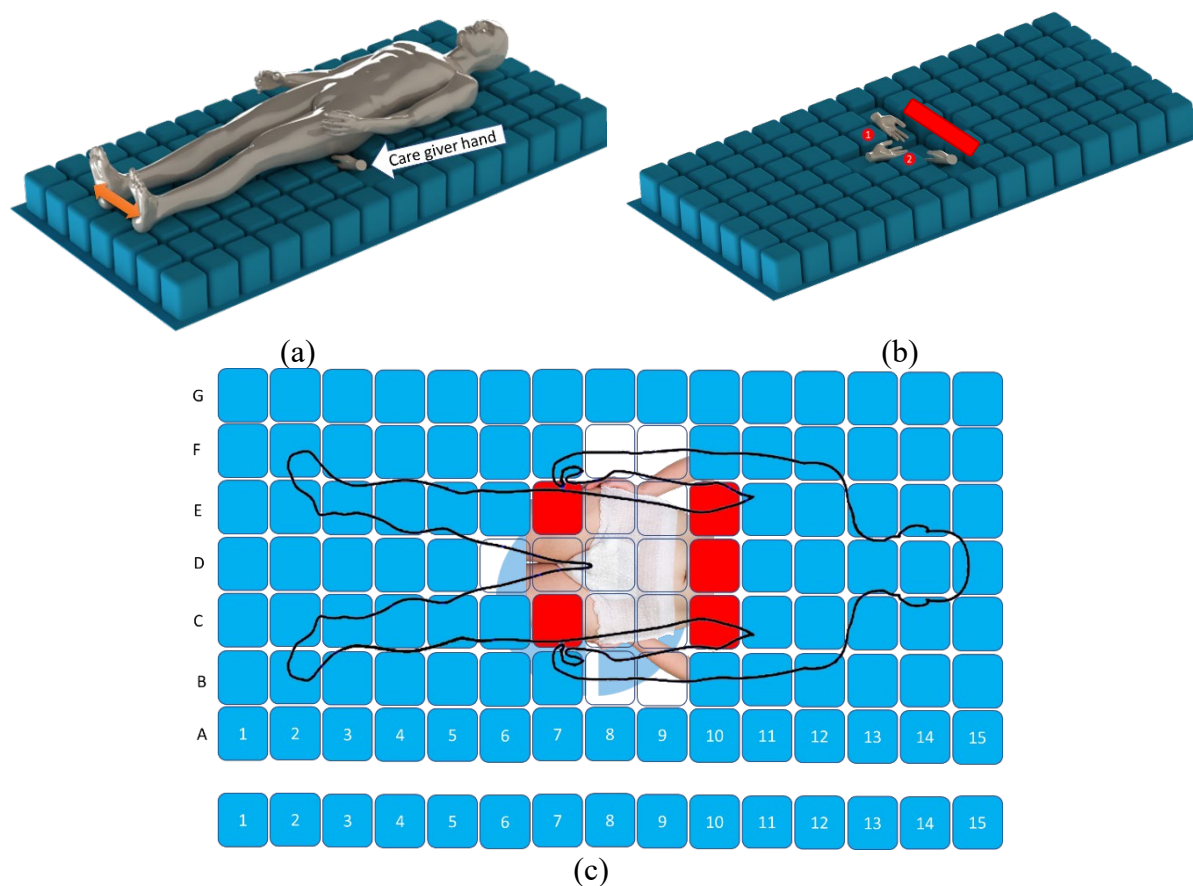


Figure 3-15. Changing diaper pose: (a) Relative position of the deflated chamber to the patient's body (b) Relative position of the deflated chamber where the hand of the caregiver can perform some operation on the patient (c) Relative position of the deflated chamber and support to the patient.

Furthermore, the position of the lower support can change the patient's pose, specifically on the lower limb, which can help the position of the genital area open wider and make the targeted space to clean easier. Another term for this pose is lithotomy position. Different support positions can change the pose, as represented in Figure 3-16. Figure 3-16 (1)

represents when the lower support is exactly on the join that makes the pose of the leg straight. Figure 3-16 (2) represents when the lower support 1/4 from the join that makes the leg pose close to the lithotomy position. Figure 3-16 (2) represents when the lower support in the middle of the thigh makes the buttock fall down to the deflated chamber space. In this case, the poses in Figure 3-16 (1) and (2) are acceptable for diaper change.

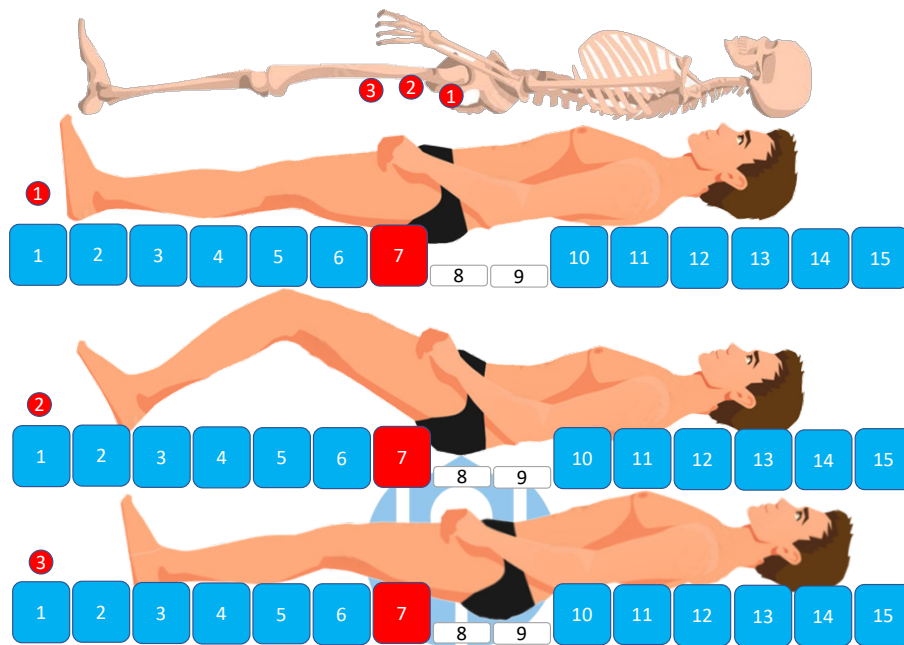


Figure 3-16. Relative positioning from side view.

3.5.3 Changing a Bedpan

The implementation can involve putting on or taking off pants, which would activate the MAM along the middle of the patient's body around the buttock. Bedpan change requires space beneath the buttock to slide the bedpan exactly in the position of urinary and defecation while keeping 3 points of support to hold the patient's limb, as shown in Figure 3-17 c. The space beneath the buttock and the way to slide it is shown in Figure 3-17 a-b. In this scenario, the case works for a larger bedpan than a chamber cell (Method A). Suppose the bedpan size is the same or lower than the deflated chamber. In that case, the bedpan only needs to be slid

inside the available deflated chamber (Method B). The red mark on the mattress supports the human body during the changing bedpan, as shown in Figure 3-17.

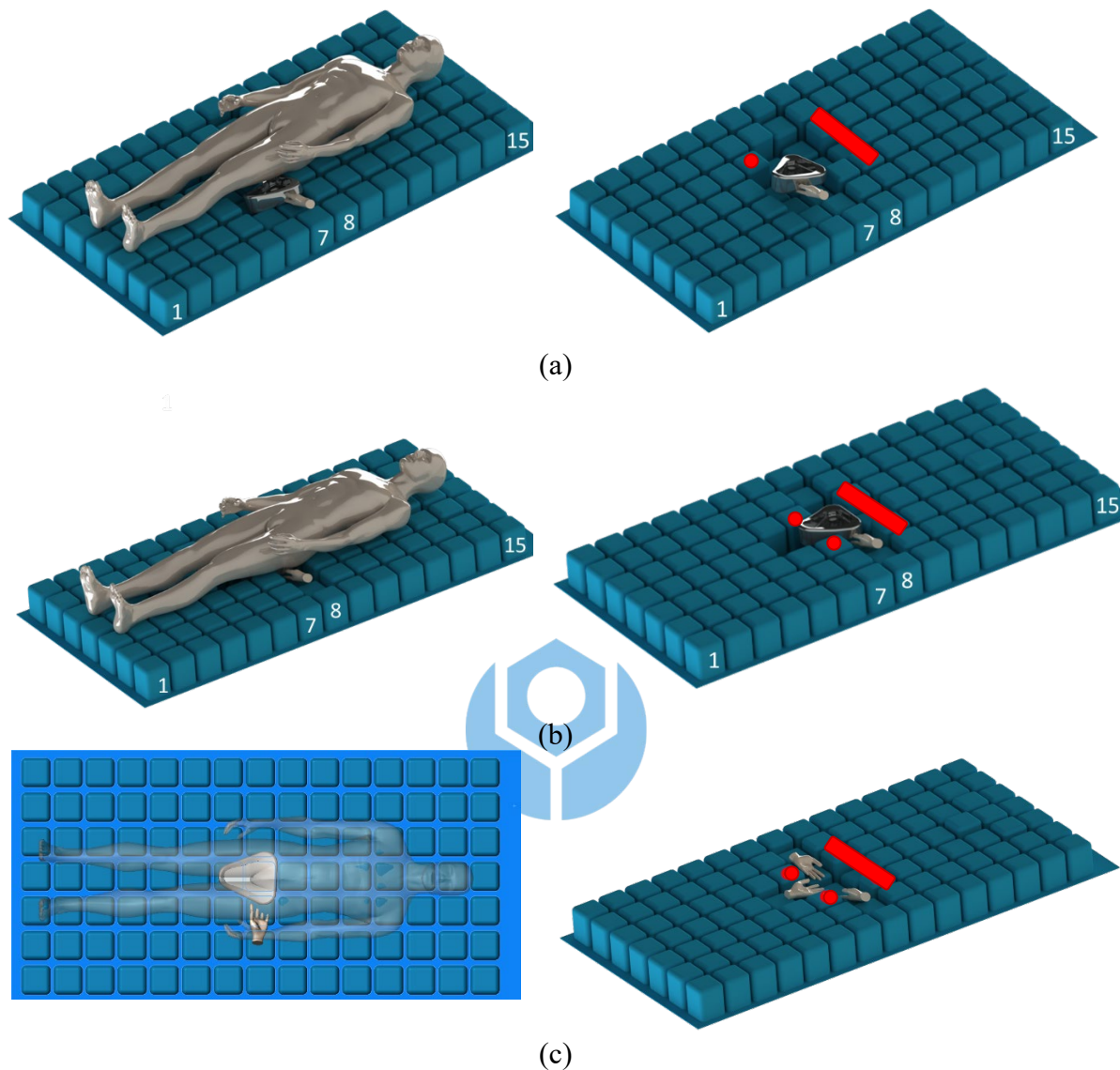


Figure 3-17. Bedpans change and defecation, Method A: the left side is perspective when the patient is lying on it, and the right side is without the patient.

Method B's approach of using a simple bedpan is proposed for a bedpan width the same or smaller than the size of the small cell. The bedpan must be slid into the mattress row along the buttock. The patient's body is supported by the mattress, which remains inflated. Figure 2-18 shows the proposed method with the following (a-c) sequence of the bedpan being slid

into the deflated chamber. At the same time, (d) is the bedpan position with respect to the patient's body. The mark on Figure 2-18 (c) is the chamber that supports the patient's body, involving the back and both thighs, left and right.

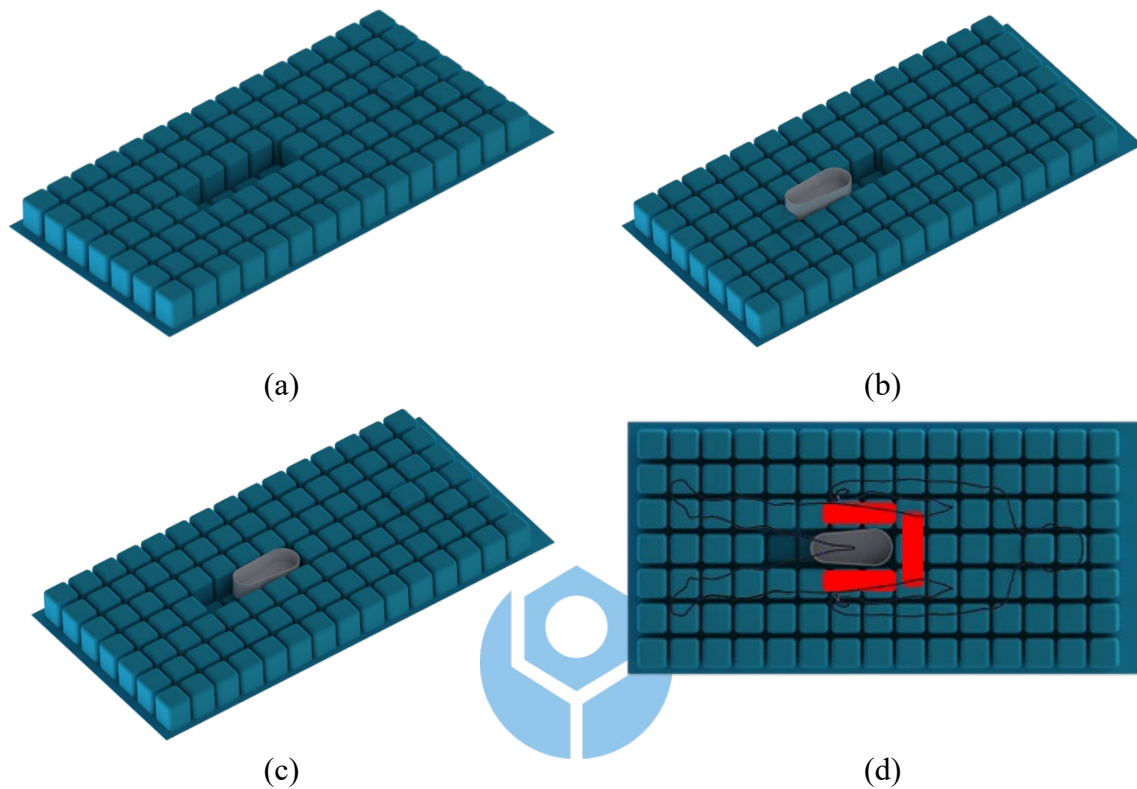


Figure 3-18. Bedpan change and defecation, Method B: (a-c) Process of sliding a bedpan, (c) Bedpan position on the mattress with respect to the patient.

3.5.4 Changing Clothes

The problem with changing clothes or dressing for the bedridden is the posture change required because the patient's body cannot be lifted easily to allow the clothes to slip away through the bottom side of the patient's body. In the proposed approach, the chamber of the mattress will be deflated according to the position required. At the same time, the part of the clothes moves through underneath the patient so that the body weight will not apply to the clothes. The wave of sequential deflation and inflation of chambers will move along the direction of cloth movement underneath the body. Deflation of a chamber creates low/no body

weight space for the cloth part to pass, while inflation of the chamber after the underneath cloth has passed generates sufficient support to keep the patient body in a constant position. The main controller controls the inflation and deflation states. Caregivers' operation hands only need to follow the inflation direction and speed.

The implementation can involve putting on or taking off pants as shown in Figure 3-19, which would activate the MAM along the lower limb part, or putting on or taking off a shirt, which would activate the MAM along the upper limb part. Each chamber of the MAM can deflate and inflate accordingly for each timeframe, depending on the task. Other tasks may require different positions beneath the patient's body to be deflated or inflated. Some specific chambers must be deflated/inflated depending on the position and characteristics of the body.

Figure 3-19 demonstrates take-off of the pants starts by deflating one chamber, number 8, then continuing to numbers 6-7 while number 8 inflated. The next chamber, 5-3, deflated simultaneously while the previous one, chamber number 6-7, inflated back. Then, it continues working like a wave until the end of the predefined position, chamber number 1. The group of deflated-and-then-inflated chambers to perform the task on a specific timeframe depends on the patient's position on MAM, which can be predefined or real-time detected. To put on the pants, the sequence reverse from Figure 3-19 (d) to (a)

Figure 3-20 illustrates the method for removing a T-shirt using the air mattress. The process begins by deflating the chamber in row 8, while the patient's hand moved up. This initial deflation is followed by a sequential decompression that moves in a wave-like pattern towards the top, continuing through chambers 13 and 15. Once these chambers are deflated, the T-shirt can be easily removed. To put on the T-shirt, the sequence is reversed. Starting from the final position shown in Figure 3-20 (d), the chambers are inflated in reverse order, ending

at position (a). This sequential inflation ensures the T-shirt is smoothly and correctly positioned on the body.

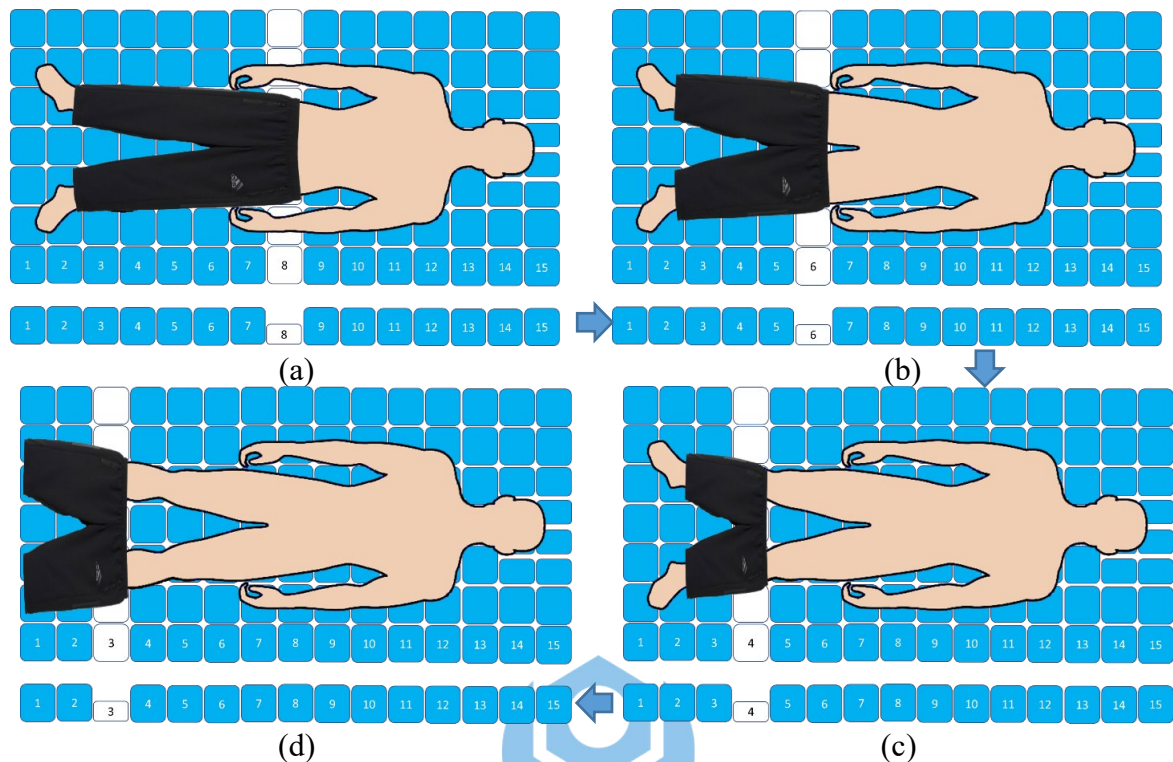


Figure 3-19. Process of changing a pair of pants.

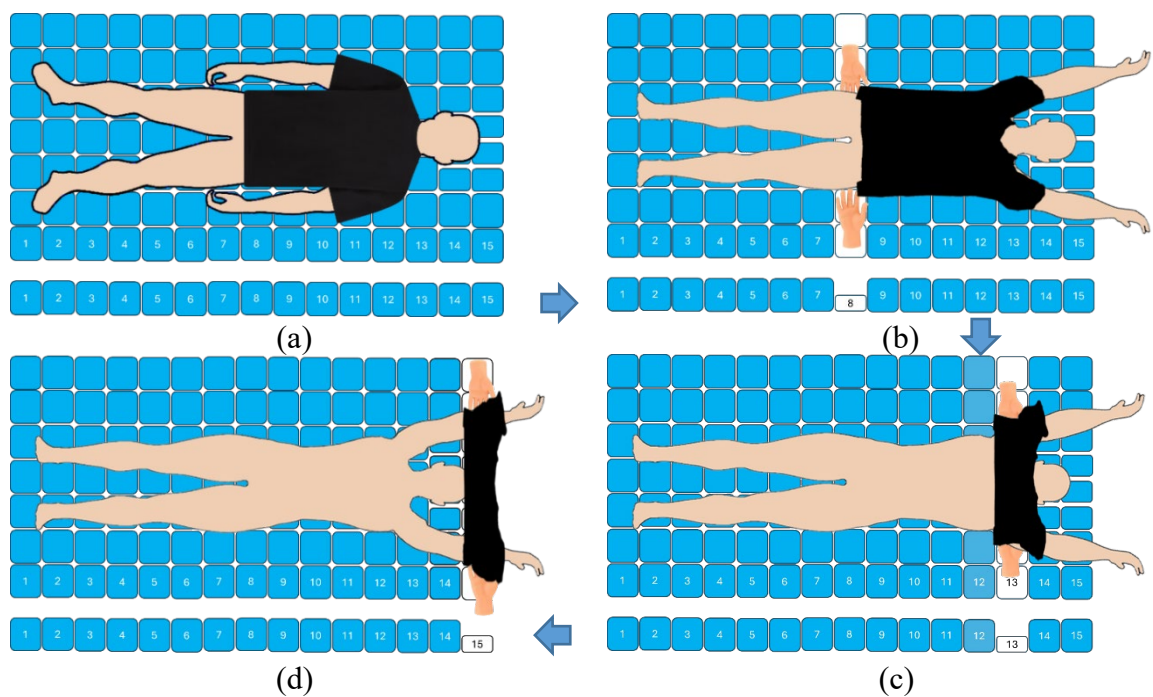


Figure 3-20. Process of changing a pair of pants.

3.6 System Evaluation

By checking the position of the patient's body, which needs to be moved or lifted during clothing changes, the performance of the proposed method will be compared with that of the conventional way [47-49, 101] and some current sophisticated methods presently available [31, 51-53]. A defined set of key points is used to represent the body sections. Each point is located in the center of mass on each body segment, as shown in Figure 3-21. These points can be used to estimate the body position during posture changes. Even if the operation must conduct repeated posture changes on the same body position or spot, the point moved will be computed just once.

In this experiment, flexible medical mannequins with a height of 175cm were used. The mannequins have been modified to have the same weight as an average human, which is 70kg. The patient's body weight is also one of the evaluation parameters.

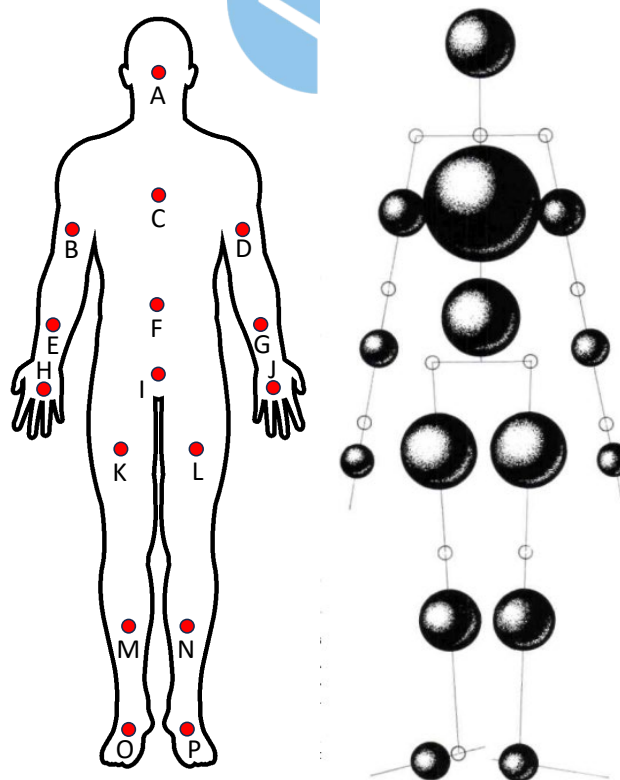


Figure 3-21. Human body segmentation is used to evaluate the performance of the dressing method: (a) Point distribution (b) Relative mass of body segment [102].

The weight distribution and relative length of the body segment are represented in Table 3-1 [102, 103]. It is related to how much force the caregiver is required to apply when changing the patient's posture, meaning lifting some body parts against gravity. The force acting on the caregiver will be estimated by calculating the moment on the patient's body while the caregiver moves the bedridden in Fowler, supine, recumbent, or lateral position, depending on the task required, as shown in Figure 3-22. Specifically, when only the hand and leg segments of the body are moved, it will be assumed as a direct lift. In Figure 3-22, W and F denote simplification of the center of mass of the patient's body and the caregiver's support position when assisting the patient, respectively. All medical terms are referred to a nursing central website, particularly the patient's position on the bed. It provides a picture representing physical activities and their names [104].

Table 3-1. Human body mass and length distribution.

Body segment	Point moved	Relative mass of body segment	Relative length of body segment
Head and neck	A	8.1%	13.5%
Arm	B, D	5.6%	18.8%
Forearm	E, G	3.2%	14.5%
Hand	H, J	1.2%	10.8%
Thorax	C	21.6%	
Abdomen	F	13.9%	33.4%
Pelvis	I	14.2%	
Thigh	K, L	20.0%	24.5%
Leg	M, N	9.3%	24.6%
Foot	O, P	2.9%	3.9%

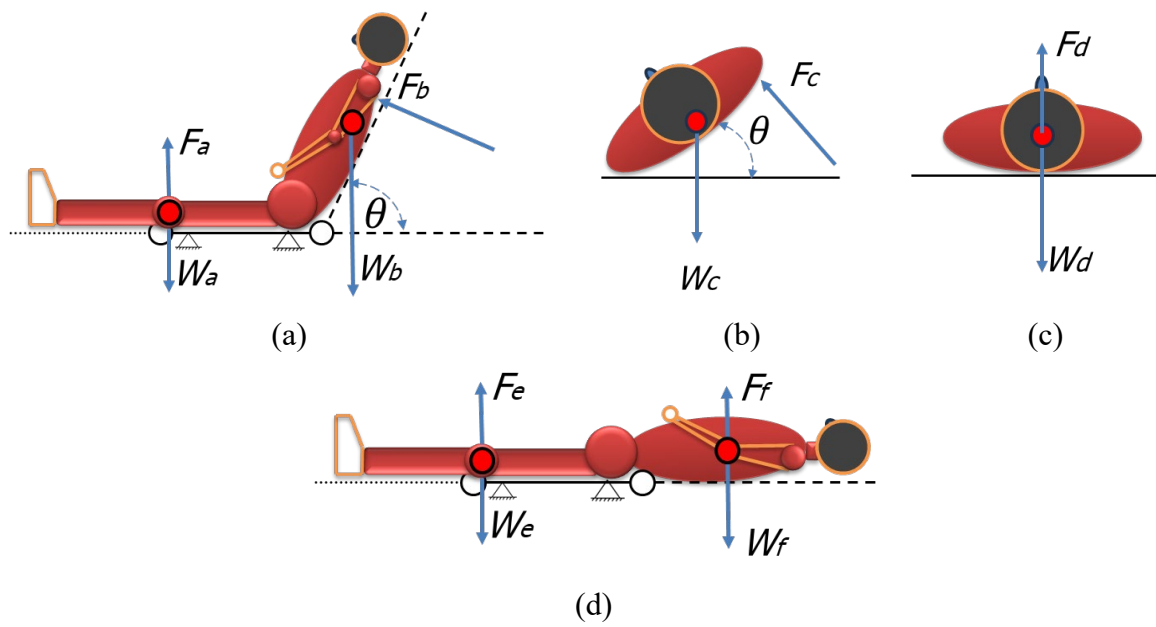


Figure 3-22. Posture adjustment in bed (a) Fowler (b) Lateral Recumbent (c) Supine, top view (d) Supine, side view.



CHAPTER 4

RESULTS AND DISCUSSION

4.1 Comprehensive Daily Care for Bedridden Individuals Utilizing Multichambered Medical Air Mattresses

In this chapter, an experiment is introduced that focuses on the execution of Activities of Daily Living (ADL) using the Multichambered Medical Air Mattress (MAM) with the assistance of a mannequin. The inflation and deflation chamber during the experiment was programmed in a predefined position according to each ADL task. The ADL tasks incorporated in this experiment encompass a comprehensive range, including dry bathing, bedpan and diaper changes, and clothes changing. The utilization of a mannequin in this experimental setup provides a simulated environment to study and evaluate the effectiveness of these daily care activities on the MAM. This experiment serves as a valuable exploration into the practical applications of the MAM in enhancing the quality of care for individuals with limited mobility.

4.1.1 Process of Dry Bathing

In the cited references [40], dry bathing is performed using a covering, such as a large towel or blanket. However, in the experiment, dry bathing is conducted with the mannequin completely unclothed (Figure 4-1) to assess the technique and algorithm of the Multichambered Medical Air Mattress (MAM). Regarding the dressing and undressing of the patient's clothes, the caregiver can use the method that is represented in subsections 4.2.4 to 4.2.7, depending on the dress the patient wears. The dry bathing process begins with the cleansing of the face using a damp towel, as represented in Figure 4-1 c. Afterward, the procedure involves wiping the entire side of the skin while in a lying position and continuing to wipe the lower surface of the skin on the deflated chamber, which provides sufficient space for hands to pass through and facilitates the cleaning process. This sequence of the process is performed from the head to the

leg, as shown in Figure 4-1 d-l. An additional note on this technique is that it still requires moving the arm to clean the armpit.

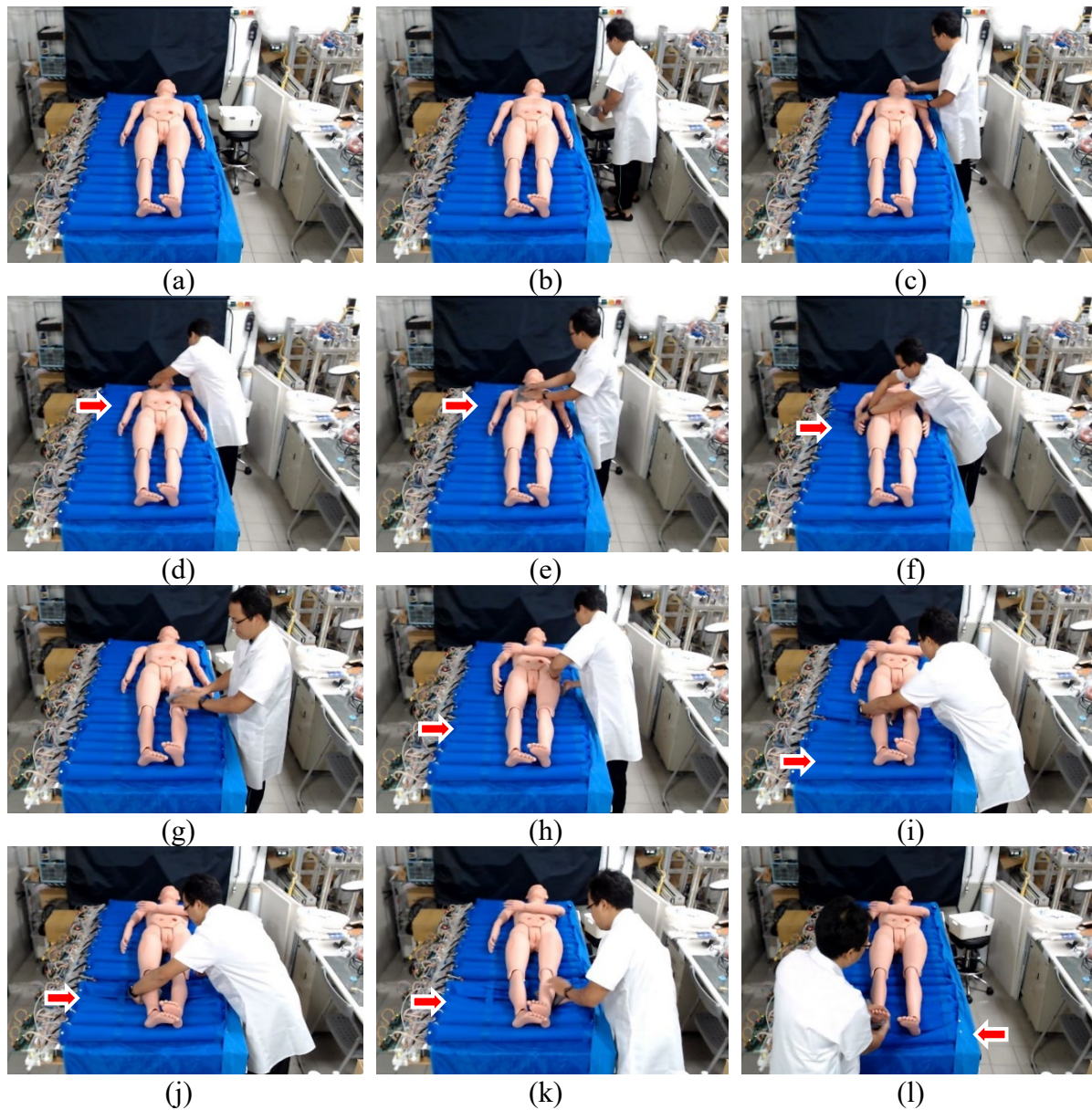


Figure 4-1. The sequence of dry bathing on one-dimensional MAM.

4.1.2 Process of Changing a Diaper

Diaper change starts by removing pants and moving the shirt upward until the cheese, as shown in Figure 4-2 a-f. The chamber from the middle of the thigh to the lumbus deflates while support on the buttock inflates, as shown in Figure 4-2 g. This one-dimensional

configuration creates space on the lumbus, genital area, and the middle of the buttock. After space is created, the back and front sides of the diaper can be folded (Figure 4-3), and the caregiver can perform the cleaning on the genital area while maintaining position of Figure 4-2 i. The caregiver can pull the diaper while checking whether there is waste in the genital area and fold or roll the diaper to prevent the waste from being scattered (Figure 4-2 i-l) while cleaning the waste. Afterward, the buttock of the patient is totally free from the diaper for further inspection and needs some treatments for further cleaning or performing some skin care (Figure 4-2 m-n). The final step to put on the diaper just requires reversing the previous task without cleaning stuff.

In the diaper-changing process, there is a crucial step which involves folding the diaper, whether for removal or when applying a new one. Improper folding of the diaper poses a risk, potentially resulting in difficulties cleaning waste, such as feces and urine, during the removal process. The recommended folding for used diapers is shown in Figure 4-3 a-f. Caregivers are required to perform cleaning procedures while removing the used diaper. During the process of removing a stained diaper, it is necessary to take specific precautions in order to avoid the waste from becoming dispersed and to guarantee that it is clean. For the new diaper, the folding purpose is to make the diaper easy to be inserted beneath the buttock as is represented in Figure 4-3 g-i.

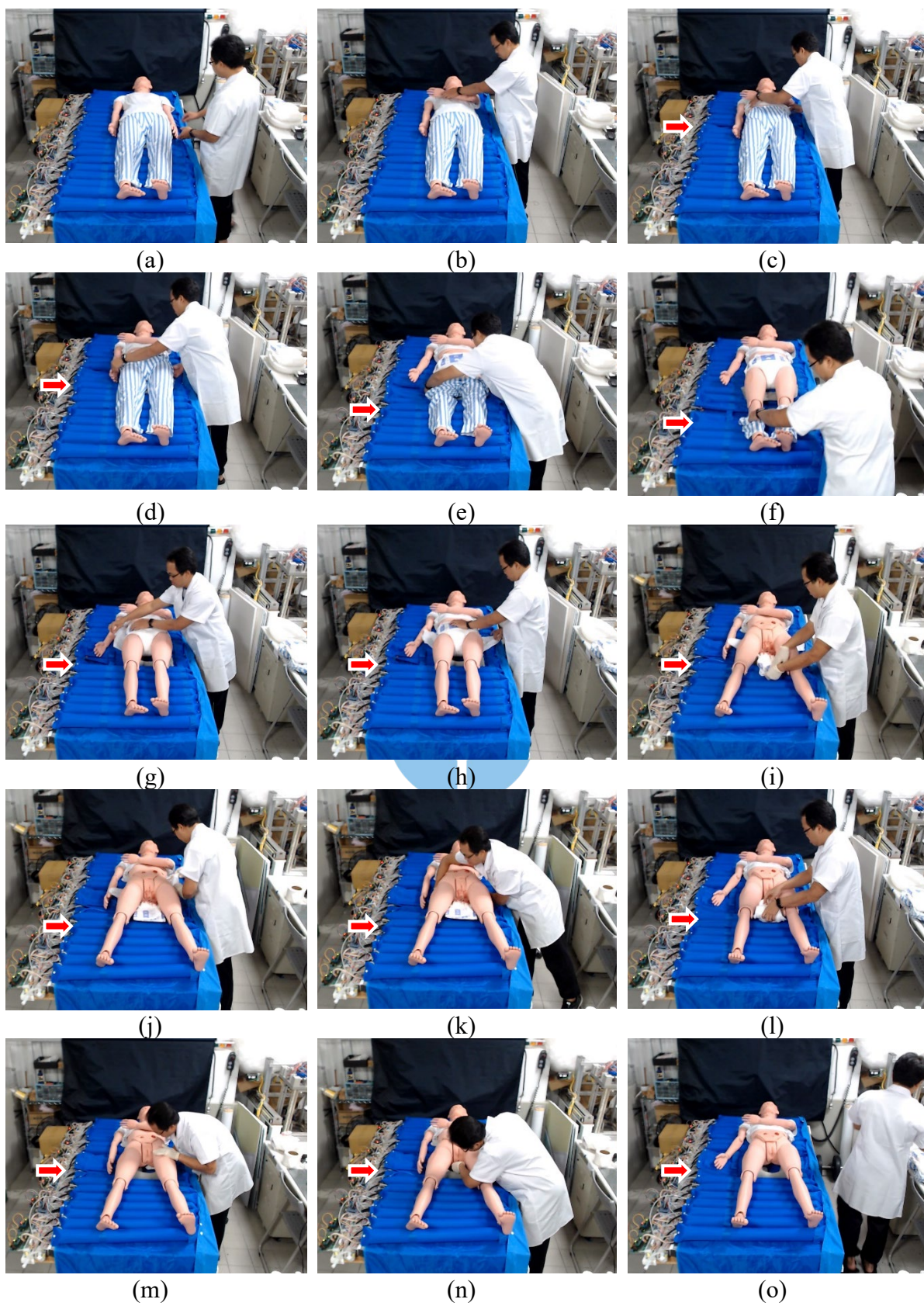


Figure 4-2. The sequence of changing a diaper on one-dimensional MAM.

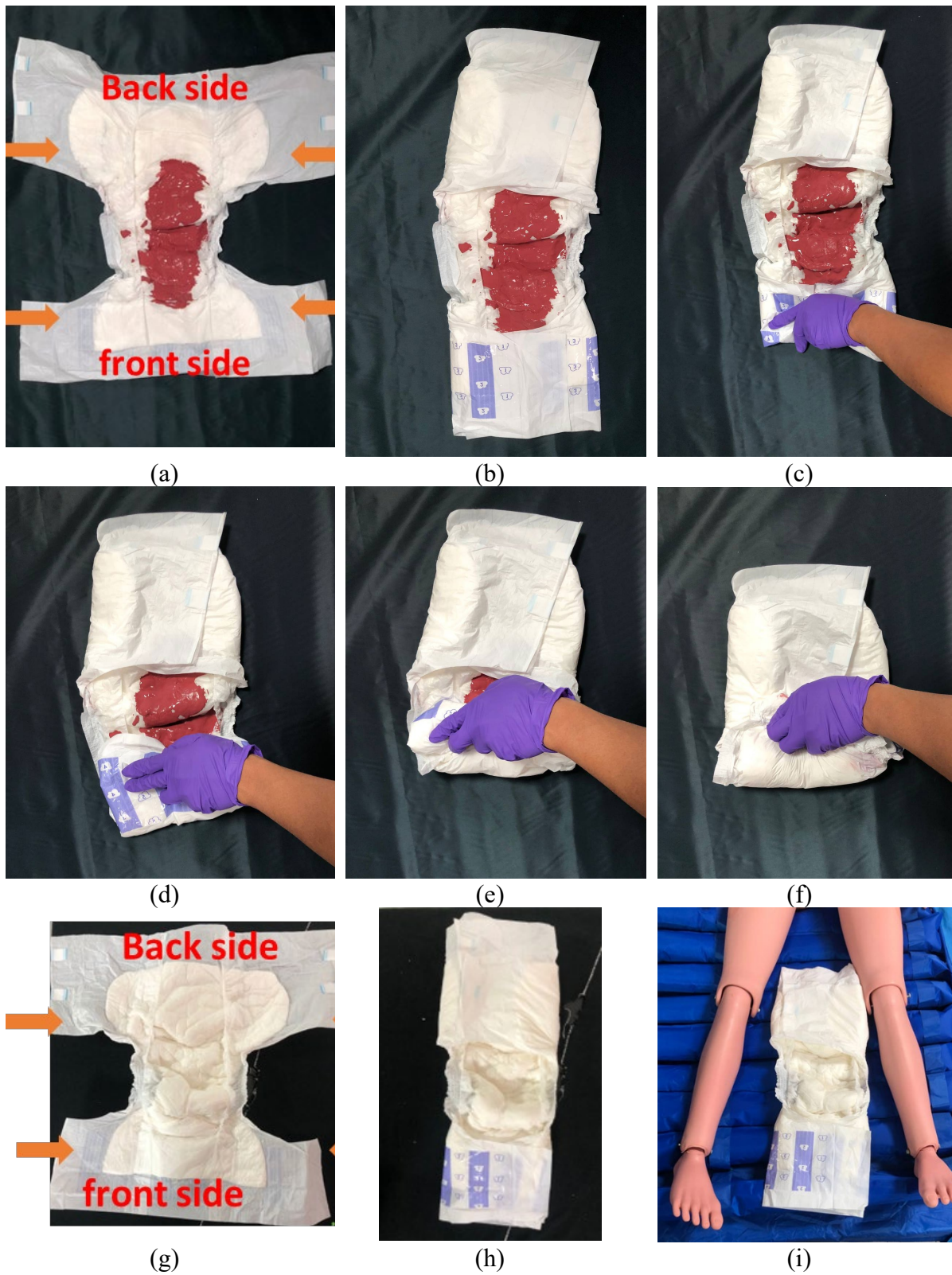


Figure 4-3. Folding the diaper: (a-f) Used diaper fold during diaper replacement and (g-i) New diaper fold during diaper replacement.

4.1.3 Process of Changing a Bedpan

The initial prototype is unsuitable for bedpan changes as the dimensions of the bedpan exceed the available space on the one-dimensional prototype. Consequently, bedpan changes are facilitated using the second prototype. The bedpan alteration in the proposed method involves a straightforward bedpan design without additional body support, as the patient's body is supported solely by the mattress, as shown in Figure 4-4. The conceptual framework section 3.5 categorizes this method as method B.

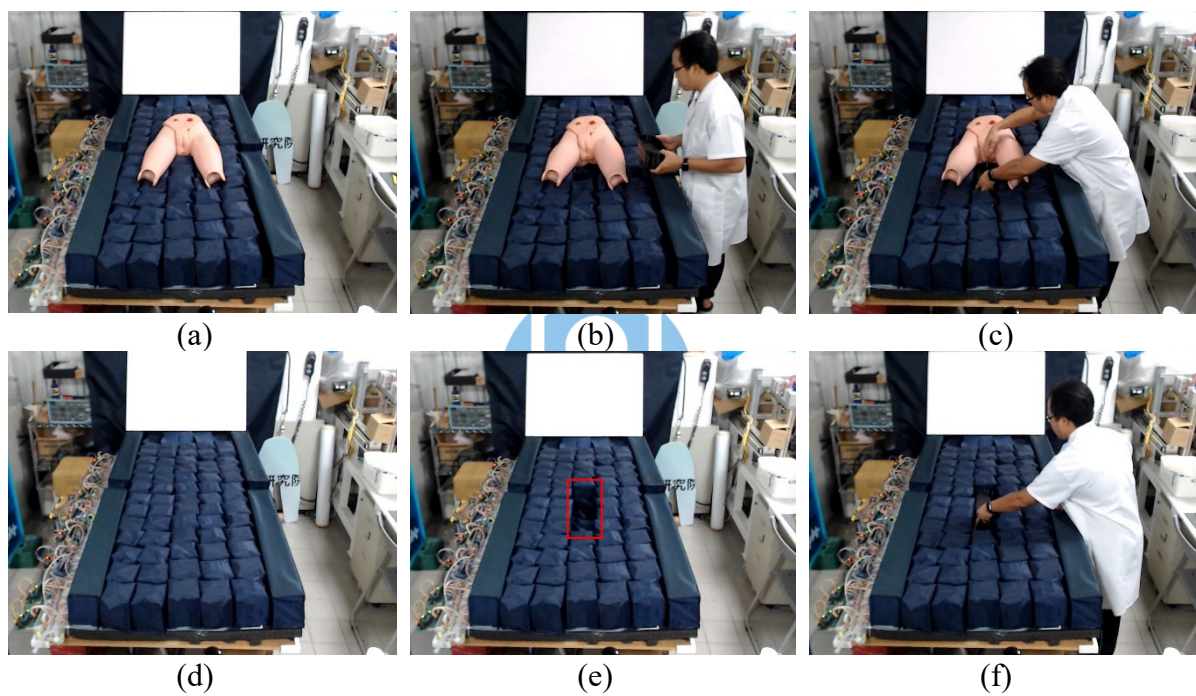


Figure 4-4. The sequence of changing a bedpan on two-dimensional MAM.

The bedpan changes start by sliding the tops to the chest and taking off the bottom following the red arrows, as the position of the deflated chamber is similar to removing clothes during the diaper change. After removing the dress, the middle chamber beneath the center of the buttock and genital area deflates, creating enough space to slide the bedpan into its space while three points of the chamber remain inflated to keep the body stationary in its position, as shown in Figure 4-4 a-c. Due to the color contrast of the mattress, the deflated chamber is not

fully visible. To improve the feasibility of the bedpan change, pictures without mannequins that show the deflated chamber are added, as represented in Figure 4-4 d-e. Figure 4-4 a and d represent the initial position of the patient before the chamber deflates. Figure 4-4 b and e represent the chamber starting to deflate the predefined position beneath the buttock of the patient. Figure 4-4 c and f represent the process of sliding the bedpan beneath the patient's buttock. After cleaning the genital area of the patient, removing the bedpan will be the reverse process of placing the bedpan.

The reason why the standard bedpan could not be used in our proposed chamber is that the design of the standard bedpan is used to support the patient's body, similar to the toilet commode, as shown in Figure 4-5 a. Then, this extra area to support the patient's body is not required in the proposed MAM. Therefore, a bedpan design that removes the body support (Figure 4-5 b) of the normal bedpan is proposed, as shown in Figure 4-5 c. To perform the experiment of bedpan change, the proposed bedpan model was printed, as shown in Figure 4-5 d.

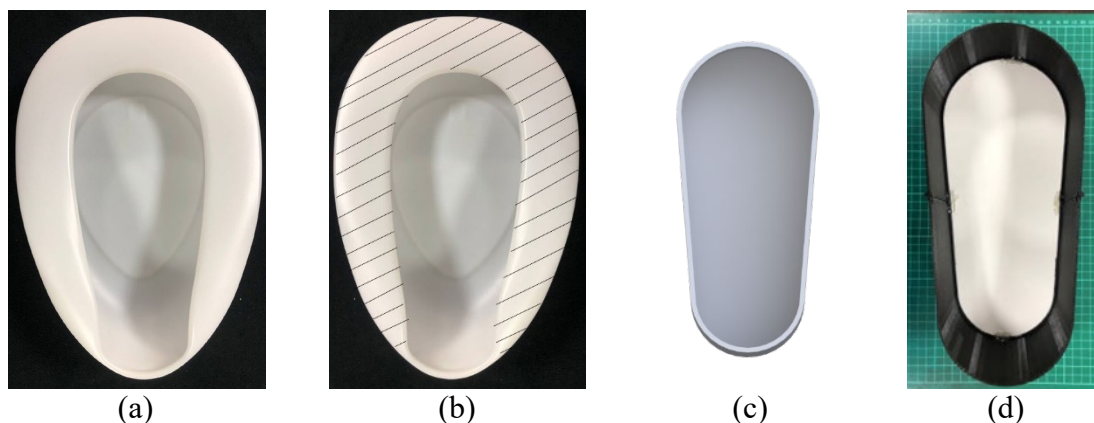


Figure 4-5. The bedpan design: (a) Standard bedpan (b) Removed part on the black mark (c) Proposed design bedpan and (d) 3D printed proposed bedpan.

4.1.4 Process of Changing a Pants

Changing a pair of pants is one of the most frequent activities for bedridden patients. Despite changing the new pants for hygiene in the daily routine, it also happens when a diaper and bedpan need replacement. The conventional method is to change the postures at all the points on the lower limb while wearing pants, either by lifting, tilting, or rotating. This conventional technique causes discomfort to bedridden patients.

Figure 4-6 shows the proposed approach for dressing pants using the proposed MAM. This technique's sequence is like when an ordinary person puts on the pants from foot to hip while supine. It starts by inserting the cuffs into the feet right and left (Figure 4-6 a-b). The underneath chambers are continuously deflated, as illustrated by the red arrow, while the caregiver follows to slip the pants beneath the patient to the hip position (Figure 4-6 c-e). Then, the caregiver must straighten the pants (Figure 4-6 f). The sequence turns back from Figure 7 f-a in a reverse sequence for taking off the pants.

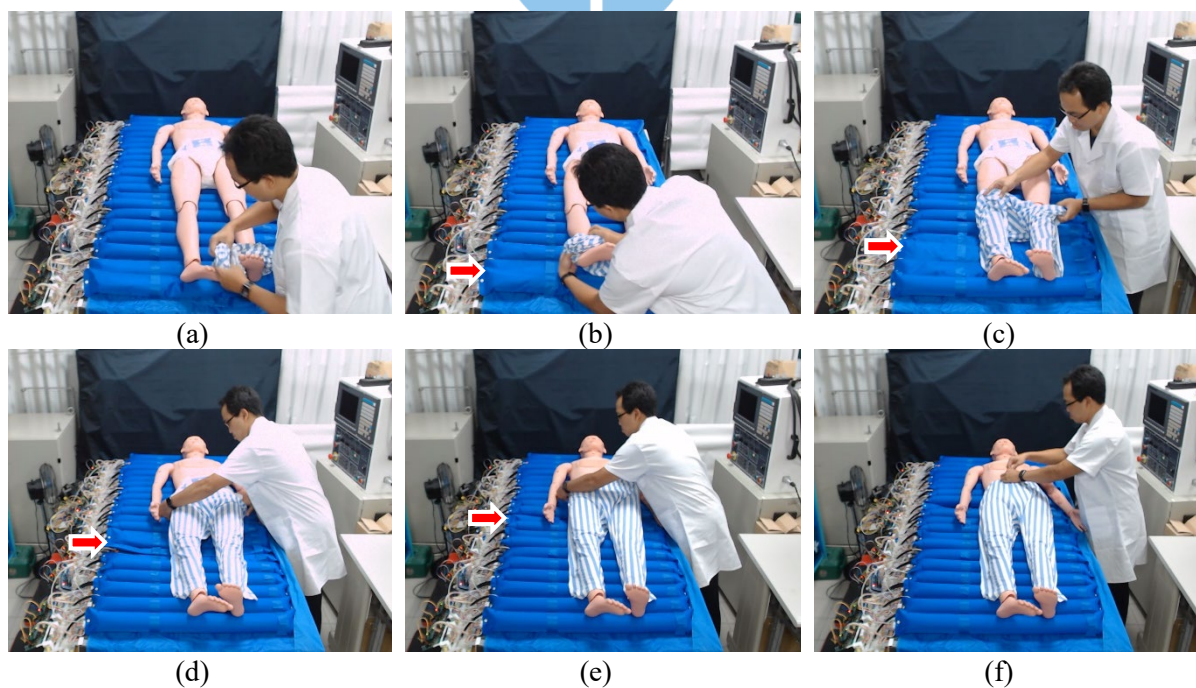


Figure 4-6. The sequence of changing pants.

4.1.5 Process of Changing a Shirt

A minimum posture change approach is demonstrated to reduce the risk of posture changes during a shirt change. Two methods are proposed in this section, as shown in Figure 4-7 and Figure 4-8, which show methods A and B, respectively. The technique uses the upper portion of MAM. The difference between the two methods, changing pants and a shirt, is the deflation-inflation wave direction, position, and a technique of switching the shirts.

Figure 4-7 shows a proposed approach to putting on or taking off the shirt from the upper body. To put on the shirt, both hands of the patient should be placed towards the top of the head position, as shown in Figure 4-7 b. Then, gently put on the sleeve on both arms (Figure 4-7 c-d). Afterward, continue by slipping the sleeve following the deflation chamber and inserting the collar beneath the head and neck of the patient. It is continued by gently slipping the shirt beneath the patient's body to the hip position following the inflated chambers marked on the arrow, as shown in Figure 4-7 f-g. Finally, the caregiver must straighten and button the shirt (Figure 4-7 h-i). To take off the shirt, the caregiver can conduct the procedure in the reverse direction.

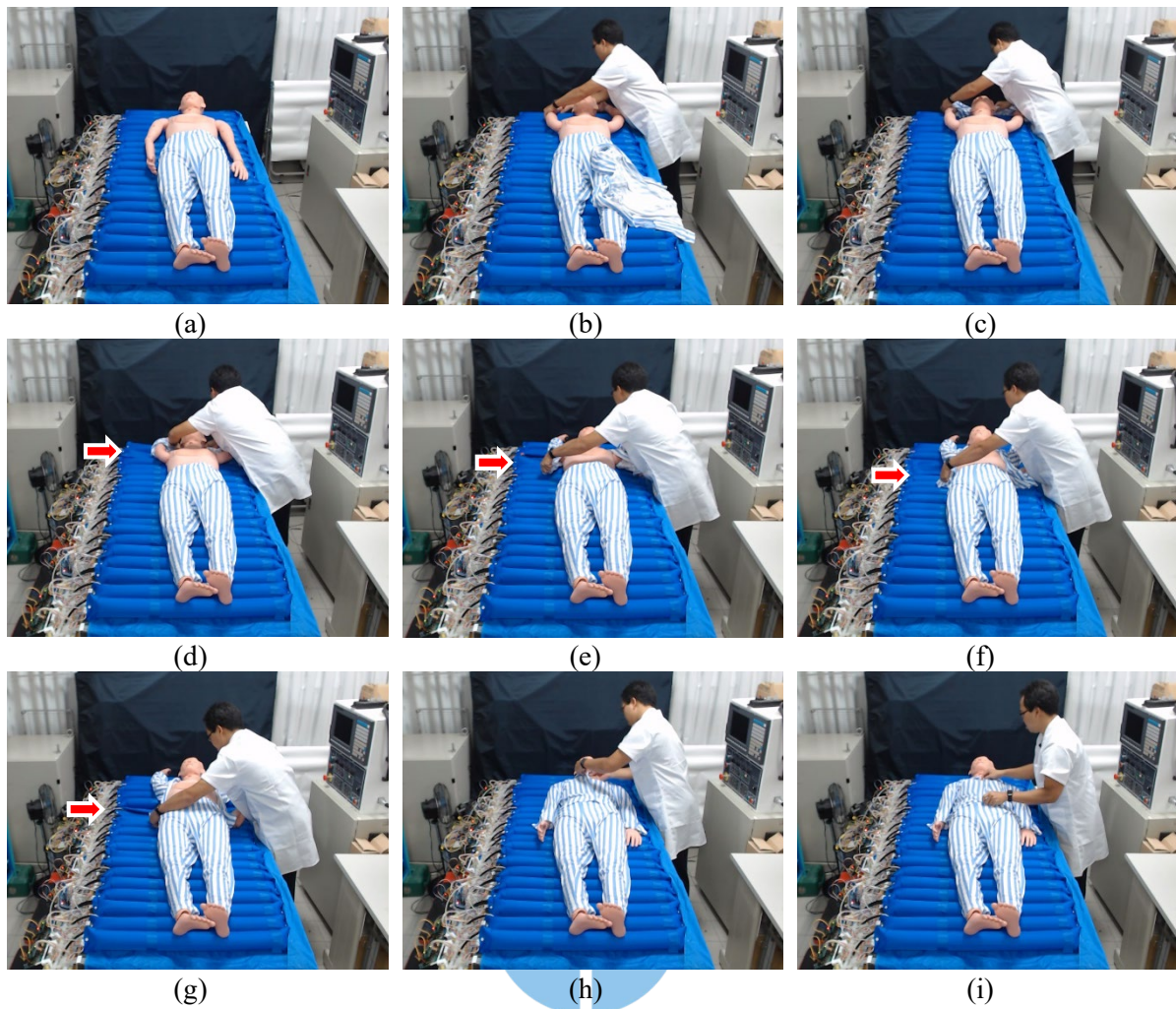


Figure 4-7. The sequence of changing a shirt, method A.

Alternatively, Figure 4-8 shows another method of changing a shirt. To put on the shirt, it starts from the hip line by putting the sleeve into the left hand (Figure 4-8 b) and then slipping another side of the shirt into the right beneath the sacrum by deflating the chamber as pointed out in the arrow in Figure 4-8 (c). Afterward, put the sleeves into the right hand (Figure 4-8 d). The shirt already on both sides is pulled up beneath the patient's body until the shoulder while managing the sleeve on both hands (Figure 4-8 e-h). The rest only needs to straighten and button the shirt (Figure 4-8 i-k). To remove the shirt, the caregiver needs to perform the reverse task of putting on the shirt.



Figure 4-8. The sequence of changing a shirt, method B.

4.1.6 Process of Changing a T-shirt

A T-shirt is one of the clothes most people are comfortable with. However, for the bedridden, the T-shirt is one of the most challenging ways to be used. Figure 4-9 shows the proposed approach to minimize the difficulty of changing a T-shirt. The red arrow in Figure 10 indicates the position of the deflated chamber. Putting on the T-shirt begins by pulling up both

hands to the top (Figure 4-9 a-b). The red arrow in Figure 10 indicates the position of the deflated chamber. Put on the T-shirt begins by pulling up both hands to the top (Figure 4-9 c-d). Subsequently, pull the T-shirt down towards the head (Figure 4-9 e-f), and finally, continuously lower it to the hips following the deflated chamber (Figure 4-9 g-h). The remaining steps involve repositioning the hands and straightening the T-shirt, as illustrated in Figure 4-9 i. Caregivers can perform the task by reversing the actions to remove the T-shirt.

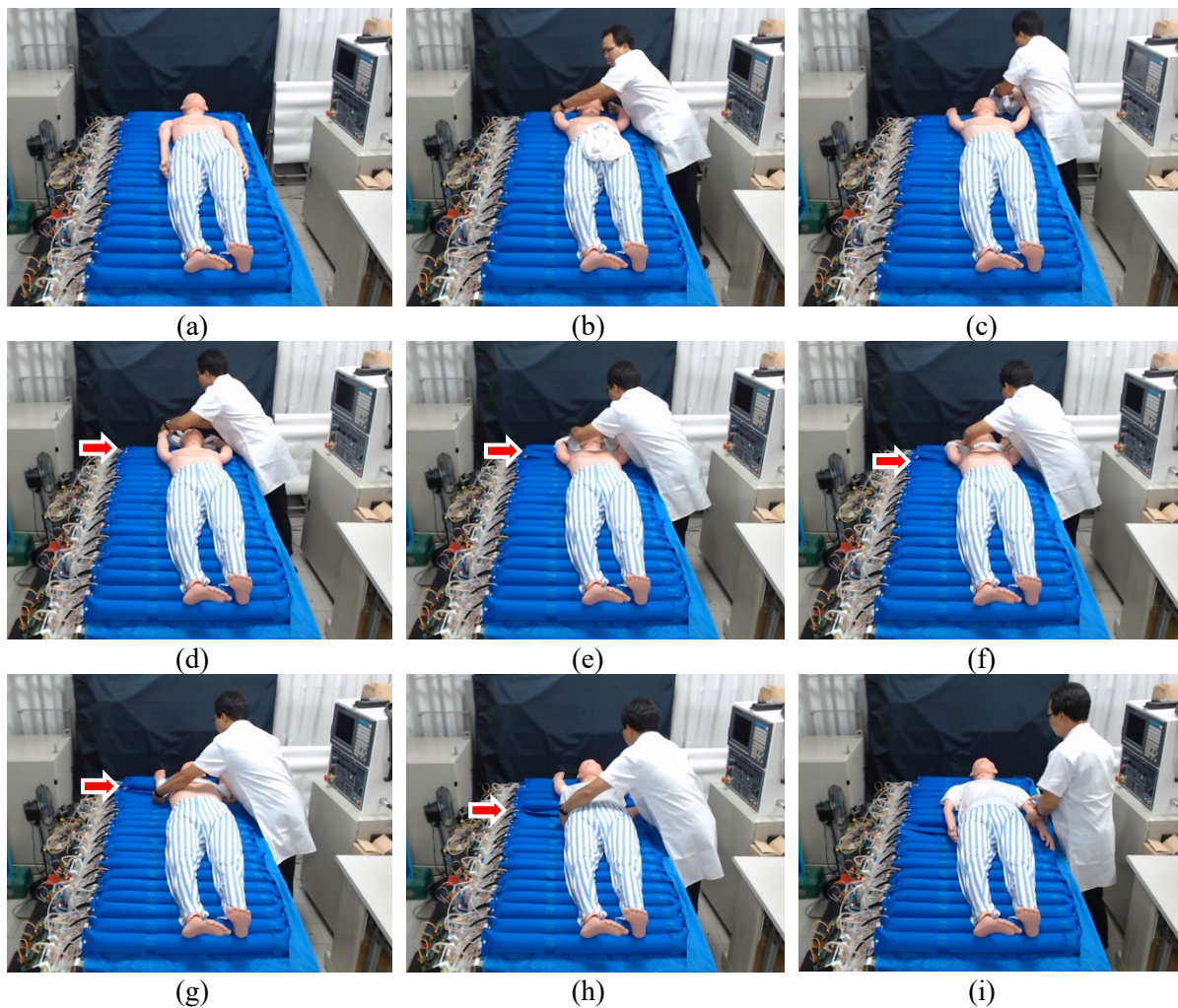


Figure 4-9. The sequence of changing a T-shirt.

4.1.7 Process of Changing an A-line

Changing a long dress is one of the most challenging tasks for bedridden patients. Figure 11 shows the proposed approach that can handle long dresses. In this experiment, an A-

line is used. There are two methods possible for dressing and undressing an A-line long dress, as represented in Figure 4-10 and Figure 4-11. The difference between the two methods is the deflation-inflation wave direction, position, and the technique of switching the A-line.

Figure 11 shows the first method of putting on an A-line, employing the dressing technique from the top side. The red arrow in Figure 4-10. indicates the position of the deflated chamber. Putting on an A-line commences by pulling up the patient's hand (Figure 4-10 b). Subsequently, gently insert each hand into the sleeves (Figure 4-10 c-d). Afterward, the collar is pulled beneath the head, managing the clothes around the shoulder area (Figure 4-10 e-f). The subsequent step, as shown in Figure 4-10 g-h, involves gently pulling down the dress till the end. Finally, in the steps shown in Figure 4-10 i-f the caregiver straightens the front side of the dress and fastens the buttons. To remove the A-line, the caregiver can simply perform the processes in reverse.



An alternative method, as shown in Figure 4-11, involves dressing the A-line from the bottom. The red arrow in Figure 4-11 indicates the position of the deflated chamber. It begins by dividing the dress into left and right sides (Figure 4-11 b), then slides the other half beneath the knee (Figure 4-11 c). Ensure the lower part of the dress is in the correct position, and then pull the dress upward following the deflated chambers (Figure 4-11 d-e). As the dress reaches the hand, insert the sleeve on both the left and right hands (Figure 4-11 f-g). Once the sleeves are appropriately fitted into both hands, continue pulling the dress upward until the collar reaches the neck (Figure 4-11 h-i). Finally, the caregivers must straighten and button the dress (Figure 4-11 j-l). To remove the A-line, the caregiver should reverse the steps above.

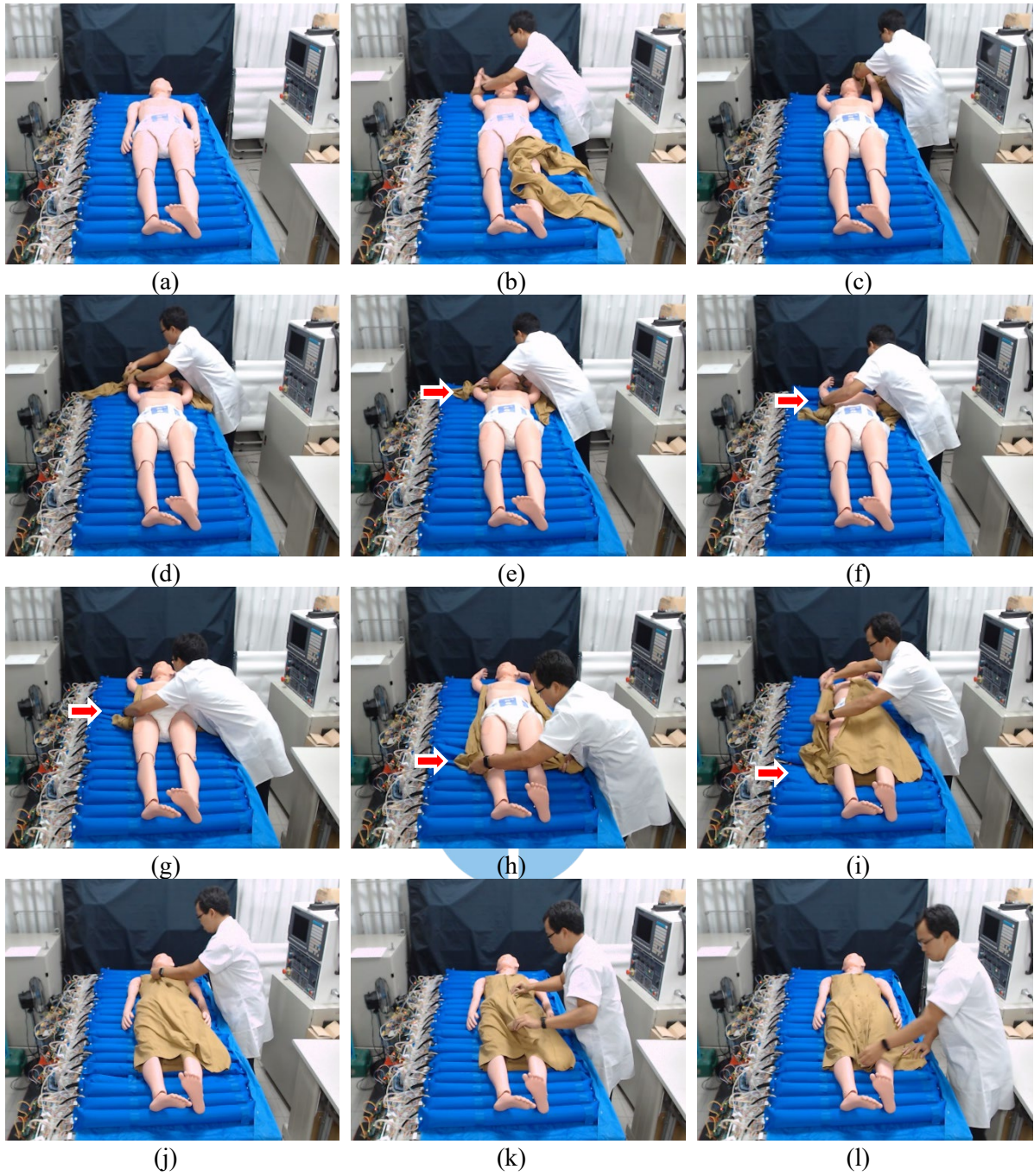


Figure 4-10. The sequence of changing an A-line, method A.

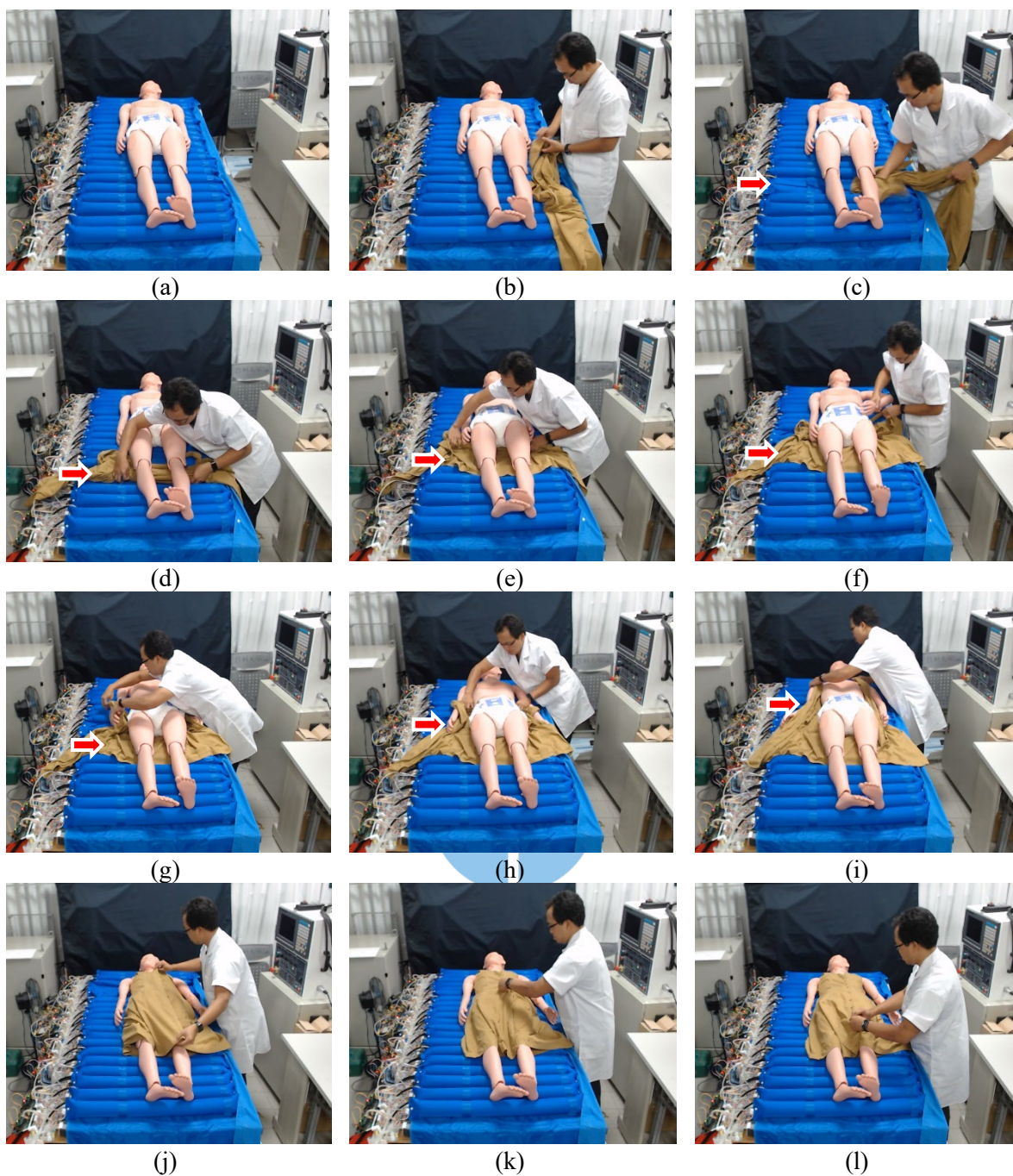


Figure 4-11. The sequence of changing an A-line, method B.

4.2 Result and Discussion

The MAM's performance and the suggested technique are assessed by comparing the number of posture changes needed in the conventional method versus the proposed approach. The discussion encompasses experiments related to Activities of Daily Living (ADL), involving dry bathing, bedpans, diapers, and clothes changes. To maintain a structured discussion, the evaluation of the proposed approach's performance is categorized into two distinct groups. The first group addresses various activities of ADL, excluding clothes change, and the second group focuses specifically on the techniques involved in clothes changing procedures as represented in Figure 4-12 and Figure 4-13, respectively.

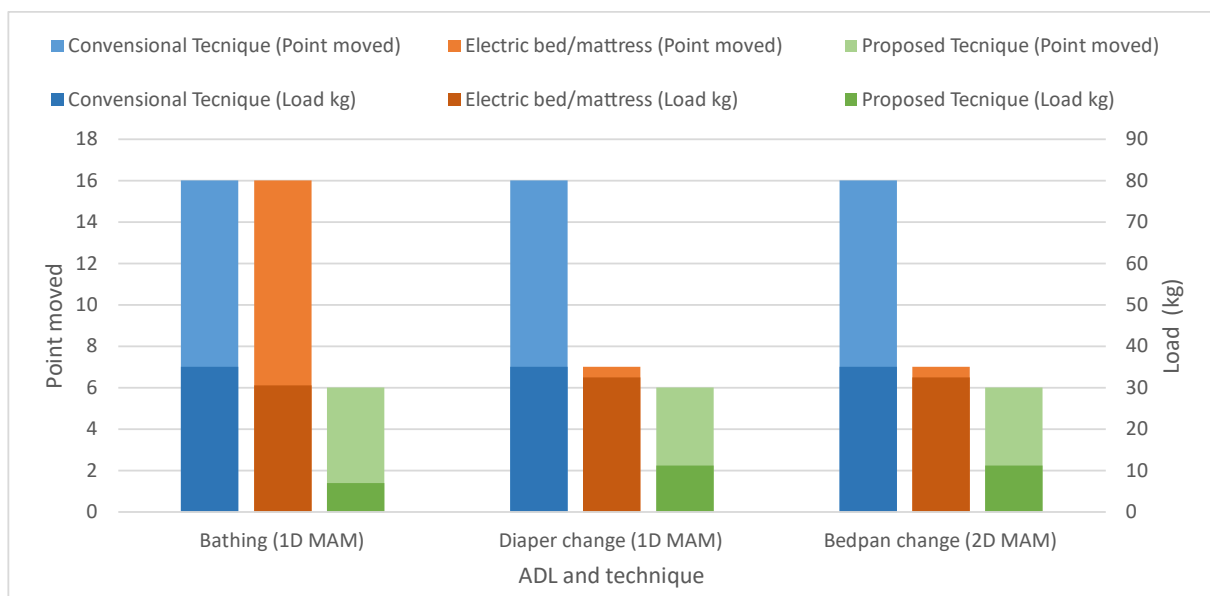


Figure 4-12. Point movement and estimated load during different tasks of bathing, diaper replacement, and bedpan change processes.

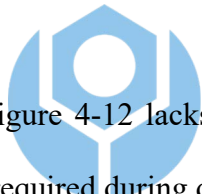
Figure 4-12 illustrates the performance of the proposed method in dry bathing, bedpan, and diaper change activities. Dry bathing in the conventional method requires full posture change to clean the patient's body. In comparison, the electric bed is not specifically available for this dry bathing. However, the reclining bed can possibly be used for dry bathing, which we include in the comparison chart. The proposed approach gives the advantages of a deflated

chamber and creates space beneath the patient's body, and the caregiver gets access to clean this area without the need for posture change, excluding the arm due to the armpit being impossible to clean without moving the arm. This means both conventional and electric beds give a posture change score of 16, while the proposed approach has 6 moving points, with an estimated load of 35kg, 31kg, and 7kg, respectively.

In diaper change, both conventional and automatic bed methods require posture changes. The posture change on both is identical. The posture change is uniform in both approaches, with the automated bed merely replicating the conventional method and shifting some of the workload to the machine. This implies that the posture change score remains identical for both scenarios, involving a total of 16 movement points with an estimated load of 35kg. In contrast, the proposed approach simplifies the process by only requiring the adjustment of the legs to facilitate easier access to the genital area for cleaning, indicating a moving score of 6 movement points with an estimated load of 11kg, as represented in Figure 4-12.

Bedpan changes are essential ADLs for bedridden patients who retain control or manage bodily functions, particularly pertaining to the release of urine or feces [41]. This task necessitates the utilization of a two-dimensional Multichambered Medical Air Mattress (MAM) due to its larger space in the deflate chamber zone. The crucial area for facilitating urine or feces release for a patient extends from beneath the genital area to the top of the buttocks. In the traditional method, the bedpan is designed to provide body support for the patient. Consequently, placing the bedpan beneath the buttocks requires a change in posture, such as adopting a recumbent position, involving a total of 16 movements. Conversely, the current air mattress designed for bedpan changes offers space beneath the patient's body. However, similar to the conventional method, it still necessitates a change in posture to a

recumbent position during the changing process. The disparity between the two techniques lies in the comfort provided to the patient. The air mattress with the bedpan feature offers improved comfort, as the patient's position remains relatively flat, in contrast to the conventional method, which elevates the patient's buttocks. This conventional method and the air mattress with the feature of bedpan change give the same score of 16 moving points with a physical load estimated at 35kg. In the proposed MAM, the patient necessitates fewer adjustments in posture, and caregivers only need to move both legs wider. This is attributed to anatomical and physiological factors. In this position, the body is in a more natural alignment, allowing the puborectalis muscle to relax and the anal canal to straighten. This alignment facilitates easier passage of stool and can help prevent issues such as constipation and hemorrhoids. The proposed approach has the result of 6 moving points and an 11kg load, as represented in Figure 4-12.



The evaluation presented in Figure 4-12 lacks a comprehensive examination of the frequency of various posture changes required during different ADL. For instance, in the case of diaper changes, some caregivers may perform the task with two recumbent positioning instances [105], while more skilled caregivers may achieve the same outcome with just one [59]. This suggests that the actual physical burden on caregivers is greater, and the discomfort experienced by the patient during ADL is substantial.

Furthermore, several experiments on clothing changes were conducted to evaluate the performance of the proposed system. The movement point and associated physical load while conducting clothes changes on bedridden patients in four clothing categories are represented in Figure 4-13. It is noted that these numbers show only the effort when putting on clothes. Taking off clothes will require almost identical point movements and physical loads but in reverse order.

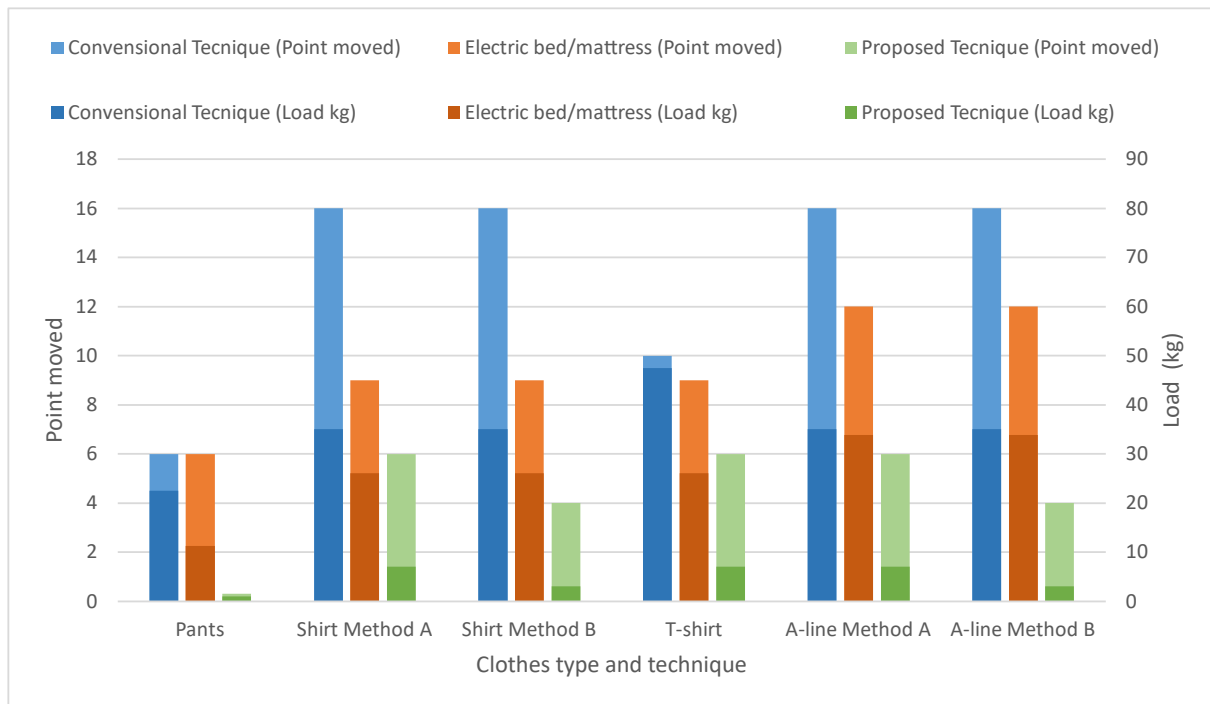


Figure 4-13. Point movement and estimated load during different tasks of the clothes wearing process.

The challenge in changing pants is to create a space beneath the buttocks. In the conventional method, the caregiver must lift the patient's kneecap to have a proper position to rotate the patient's buttocks side by side while removing or putting on the pants [49]. Another method uses a tilting bed to change the posture into a lateral position that mimics the conventional method. With this tilting bed, caregivers require less force to change the patient's posture on the lower limb to slide the pants side by side [31]. However, both conventional and electric bed approaches require 6 moving points, meaning 6 body parts must be repositioned to complete the pants change task. To overcome the limitations of those methods, the proposed approach provides the required space beneath the lower limb in time while changing pants. In this case, no posture change is needed, which means the number of moving points is zero. It indicates that the proposed method eliminates entirely the workload of caregivers regarding the patient lift or rotation while the load for the conventional method and the electric-bed approach is 23 kg and 12 kg, respectively, as shown in Figure 4-13.

A shirt or blouse is common and relatively easy to wear for bedridden patients. In the conventional method, the caregiver needs to change the posture of the bedridden to be lateral and then put the shirt on the patient side by side. The process needs careful care because the patient's body must be tilted to a lateral position [49]. Furthermore, the bedridden on the electric bed must change the posture to Fowler's position. At this point, the patient needs to be pushed forward to give away space to slide the patient's shirt behind the body [51-53]. As a result, each method has different moving points, 16 and 9, resulting in a load for the caregiver of about 35 kg and 26 kg for conventional or electric beds, respectively. Otherwise, the proposed approach only requires posture change on both patients' arms. There are two possible methods in which both hands must be repositioned to get the sleeve into the hand. The mattress alternates from the top to the middle to get the changing shirt done, as represented in Figure 4-7. Additionally, the second method only requires alternating the mattress on the upper limb, as shown in Figure 4-8. Both methods significantly reduce the moving point to 6 and 4, resulting in a load for the caregiver of about 7 kg and 3 kg for method A and B, respectively.

The constraint of changing T-shirts is more severe than changing a shirt. In the conventional method, it is almost impossible without discomforting the patient during some manipulations. As demonstrated in the ALS Association channel, the caregiver changes the patient's T-shirt by forcing the patient to lift their upper limb body an inch in a short period of time until the shirt reaches the soldier area. Then, the caregiver removes the sleeves side by side and lifts the shoulder to take off the T-shirt [47]. Changing a T-shirt is also possible in an electronic bed by using the same method as a shirt change. Each method of the conventional and the electric bed has the same number of moving points 11, but has different loads due to the positioning method, resulting in loads of about 47 kg and 26 kg, respectively. In the proposed approach, the caregiver only needs to perform hand positioning, as demonstrated in

Figure 4-9. In the same way as shirt changing, the number of moving points is only 6, and the caregiver loads only about 7 kg.

The long dress is an ordinary dress used by women. Bedridden females mostly lost their freedom to use it due to difficulty changing the long dress. For evaluation, A-line is used as a demo. In terms of design, the A-line is like a shirt or blouse but has more extended waist and leg covers and short sleeves. In the conventional method, wearing an A-line will be the same as wearing a full-body dress like a shirt and pants [48]. Even for electric beds, three-quarters of the body needs to be repositioned to put on the dress, and for the lower part of the A-line, the dress must slide underneath the patient's buttocks. According to the investigation, conventional and electric bed techniques require body posture change, which has 16 and 12 moving points, resulting in a load of about half the body weight. The proposed technique for changing an A-line is the same as a shirt change, which can be done using two methods. The first method, changing from the top, means the caregiver needs to position the patient's hand to pull the sleeve into the patient's hand, then slightly pull down the dress from the head to the leg, as shown in Figure 4-10. Another method is to put on the A-line from leg to neck. This proposed technique only requires the patient's arm to be inserted appropriately into the sleeve, as shown in Figure 4-11. Compared to the first method, the second proposed approach does not need to manage the patient's head. Each approach has minimum points moved, 6 and 4 points for method A and B, resulting in a load of about 7 kg and 3 kg, respectively.

According to the moved point and load analysis mentioned above, the proposed method significantly reduces the physical load of caregivers on bedridden patients during clothing changes. The dressing approach also successfully replaces awkward positions by keeping simpler postures on each dressing technique and effectively reduces friction on the skin by creating extra spaces while sliding the clothes underneath the patient, making the dressing

process almost effortless. Furthermore, the difference in patient body weight distribution does not affect the proposed approach's performance because it works without moving/lifting the patient's body.

The analysis shown in Figure 4-13 does not include the frequency of all posture changes needed in different clothes changes. For example, to dress a shirt or a pair of pants, the patient will be repositioned twice in a lateral position on the left and right sides to put on the shirt or pants properly [46], while a skillful caregiver may complete the process on one side [49]. It indicates the caregiver load could be greater or even twice, and discomfort for the patient is more significant than what was shown in Figure 4-13. Nevertheless, our proposed technique does not require frequent posture changes compared to other methods.

Furthermore, the prototype, whether a one- or two-dimensional air mattress, possesses the fundamental capability to perform alternating inflation for bedsores prevention. The additional functions proposed in this study include bathing, diaper changing, using a bedpan, and dressing and undressing clothes are contribution of this dissertation. The experiment demonstrates that the objectives of this study have been successfully achieved.

4.3 Study limitation

An important consideration in this research is the limitation that medical mannequins may not accurately replicate the dynamic and varied responses of actual bedridden patients during ADL procedures. Real-life situations involve subtle motions, adjustments, and personal responses that mannequins may not completely emulate. Factors such as caregiver-patient interactions, environmental influences, and unforeseen problems may not be fully reflected in clinical practice. The following points are limitations of using medical mannequins for ADL experiments:

- 1) **Lack of Dynamic Response:** Medical mannequins may not accurately simulate the dynamic and varied responses of actual bedridden patients during ADL procedures. Real-life scenarios involve subtle movements, adjustments, and individualized responses that mannequins may not fully replicate.
- 2) **Skin Texture and Sensation:** Mannequins might not accurately represent the diverse skin textures and sensitivities encountered in bedridden patients. Assessing the impact of the ADL technique on the skin, including potential irritations or discomfort, may be limited by the artificial nature of mannequin skin.
- 3) **Body Contour Variations:** Bedridden patients exhibit a wide range of body shapes and contours. Mannequins, even if adjustable, might not fully capture the diversity encountered in a real-world patient population, potentially affecting the applicability of the ADL techniques.
- 4) **Limited Interaction:** Unlike human subjects, mannequins lack the ability to provide feedback or express discomfort. Understanding the patient's experience during ADL procedures, including any subtle signs of discomfort, may be challenging with mannequins.
- 5) **Psychological and Emotional Factors:** Dressing experiments involving real patients consider psychological and emotional aspects. Mannequins do not replicate the emotional responses, anxiety, or stress that patients may experience during the ADL process, limiting the assessment of the holistic impact.
- 6) **Generalization to Clinical Practice:** Findings from dressing experiments using mannequins may have limitations when extrapolated to real clinical settings. Factors such as caregiver-patient interactions, environmental influences, and unforeseen challenges in clinical practice may not be adequately captured.

While medical mannequins offer controlled and standardized conditions for experiments, these limitations should be considered when interpreting and applying the results

to real-world scenarios with bedridden patients. Future studies may explore complementary methodologies to address these limitations and enhance the validity of ADL experiments.



CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

The experiments successfully showcase the feasibility of performing Activities of Daily Living (ADL) with the Multichambered Medical Air Mattress (MAM), whether utilizing the one-dimensional or two-dimensional model. A thorough analysis of each ADL category highlights a significant positive effect of the proposed MAM, enhancing comfort in ADL and simultaneously reducing the physical strain on caregivers.

The challenges and physical strain encountered during the process of ADL for bedridden patients can adversely impact patient comfort and lead to occupational injuries for caregivers, especially with frequent operations. In response to these issues, this study introduces an innovative system for conducting ADL, collaborating with the chamber deflation-and-inflation sequences of the Multichambered Medical Air Mattress (MAM).

In detail, the proposed bathing technique significantly mitigates the necessity for frequent posture adjustments throughout the bathing process, consequently reducing the physical strain imposed on the caregiver. Moreover, the alteration of the bedpan becomes more facile for the patient and assumes a more straightforward task for the caregiver. The most formidable task, namely the diaper change, manifests a substantial positive impact on both the bedridden individual and the caregiver, attenuating the physical burden entailed in the diaper-changing process while upholding the prescribed standards of hygiene.

The proposed method underwent testing with various types of clothes, including pants, T-shirts, shirts, and A-line dresses, without requiring any modifications, allowing for the use of regular clothes. The analysis reveals that the suggested approach significantly reduces

caregivers' physical loading by an average of 80% and minimizes patient discomfort by eliminating the need for frequent posture changes during clothing changes. This technique contributes to an improved quality of life for bedridden individuals, enabling them to change clothes more frequently without concerns about causing occupational injuries to caregivers.

5.2 Future Work

Many issues regarding the operation speed of the air mattress, the sensing system, the mechatronics design, and the intelligent modules that enable autonomy are under investigation. In detail, the forthcoming endeavors within this research encompass the following:

- 1) Develop a Graphical Human Interface to help caregiver interact with air mattress.
- 2) Addressing potential leakage issues in the mechanical components.
- 3) Resolving concerns related to the speed of inflation and deflation.
- 4) Tackling challenges associated with weight distribution detection.
- 5) Streamlining the controller and wiring complexities.
- 6) Securing approval for human trial commencement.
- 7) Implementing precise control mechanisms to enhance patient comfort during alternate chamber utilization.
- 8) Executing an autonomous system integration.

It is imperative to acknowledge that the prototype is in the early stages of development, necessitating additional efforts for eventual market availability and compliance with safety standards for assistive devices. Our ultimate objective is to establish a fully autonomous human-machine collaboration system, optimizing interaction between caregivers and bedridden patients.

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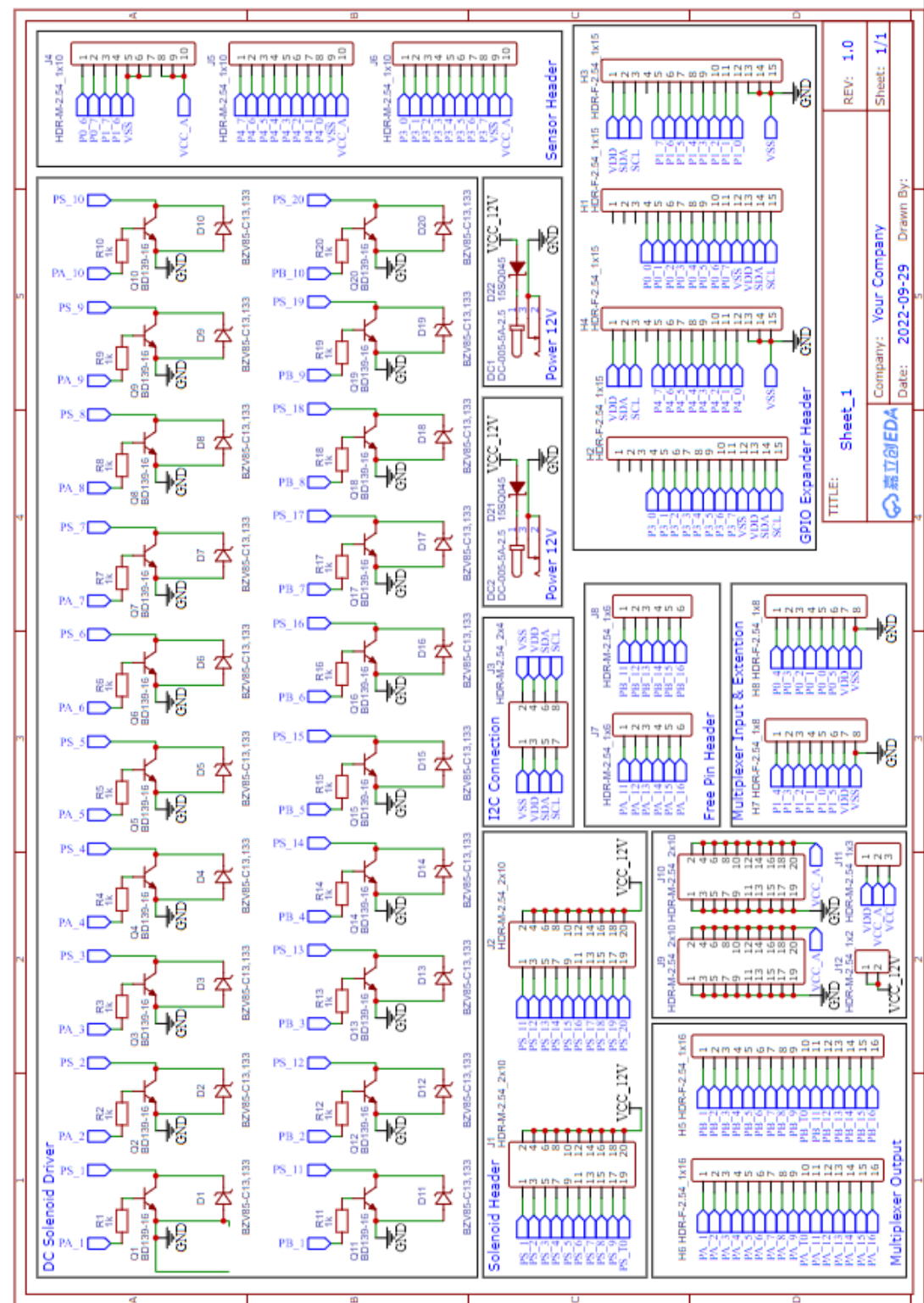
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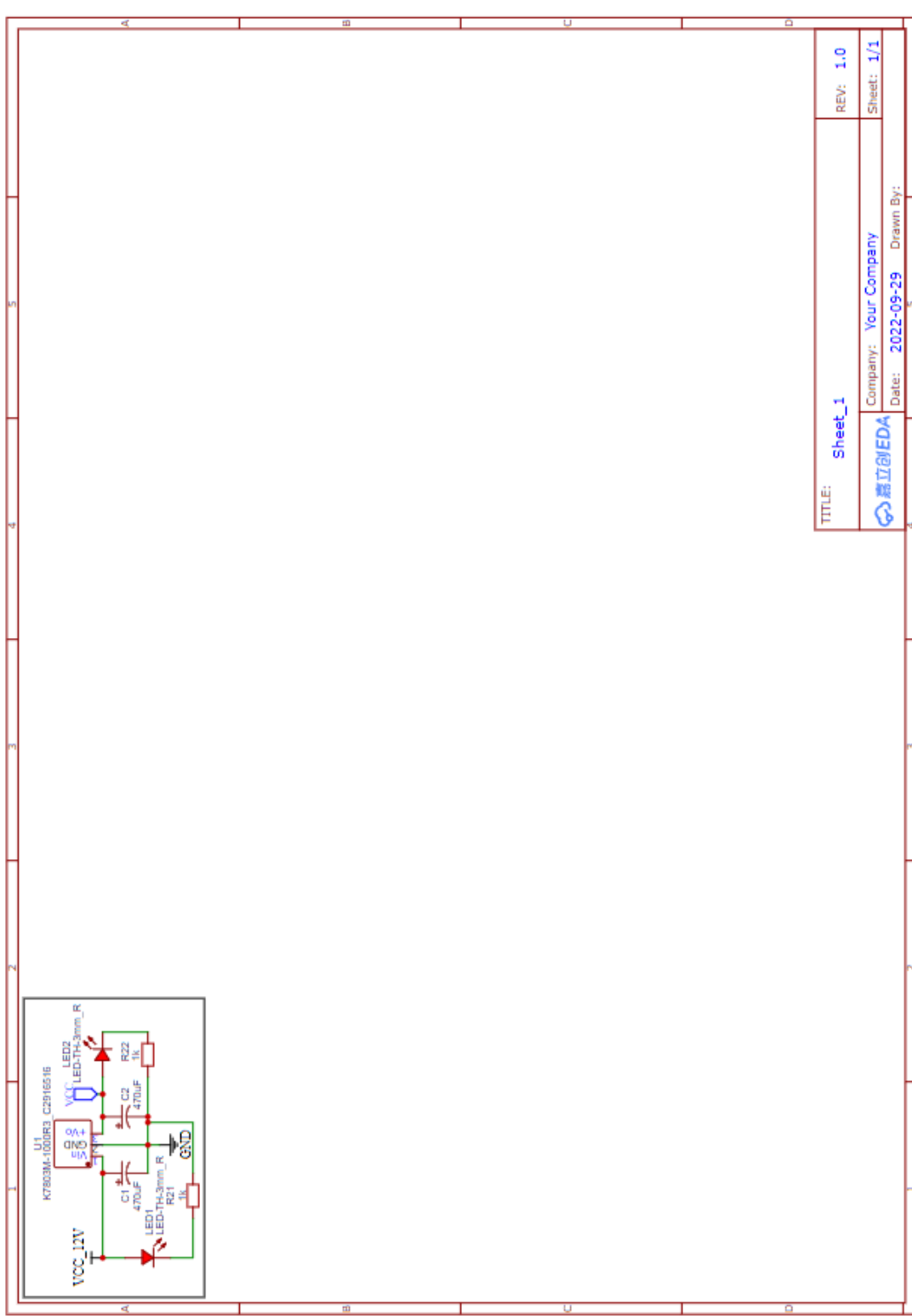
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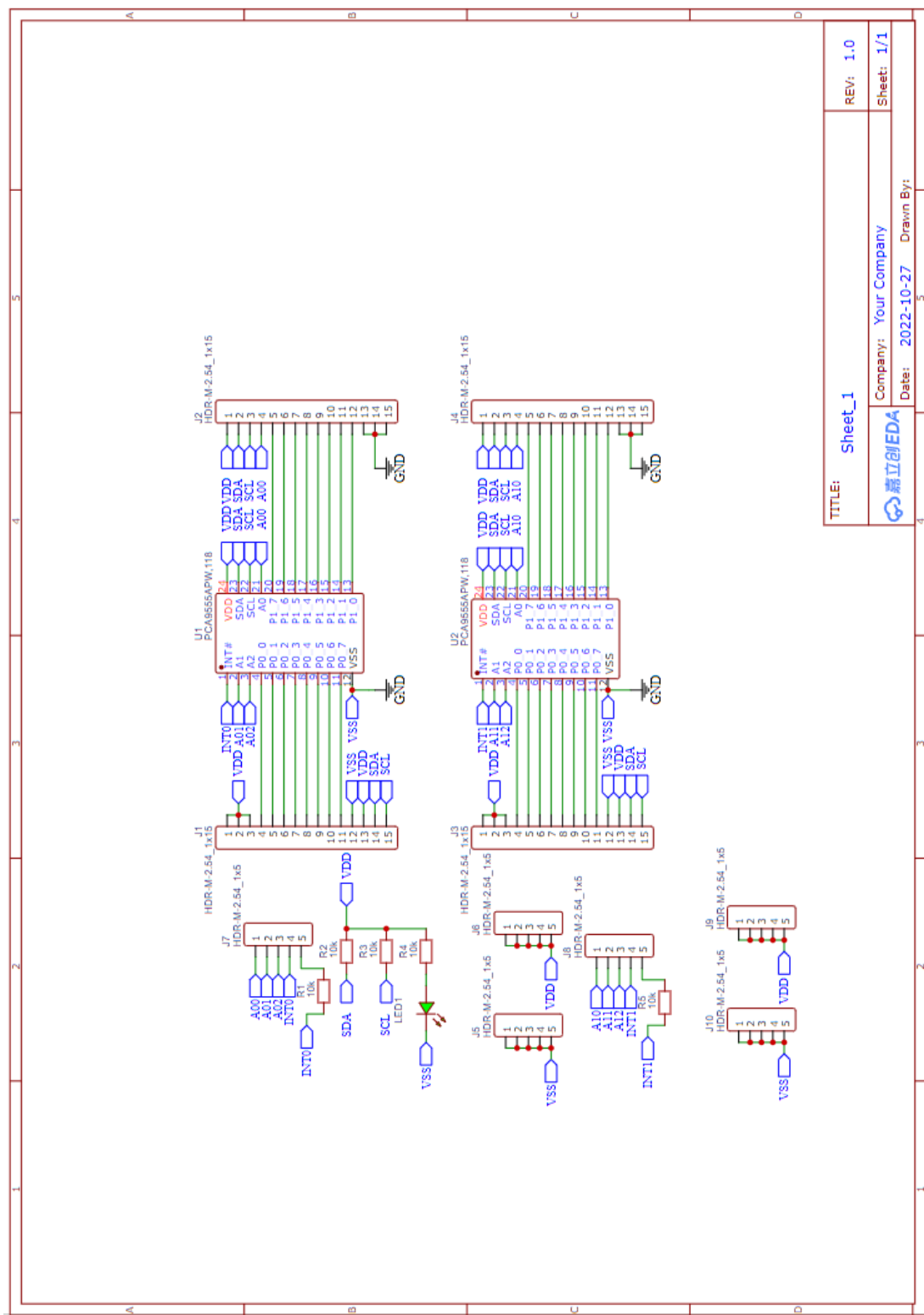
APPENDIX

A. Electronic design: Driver

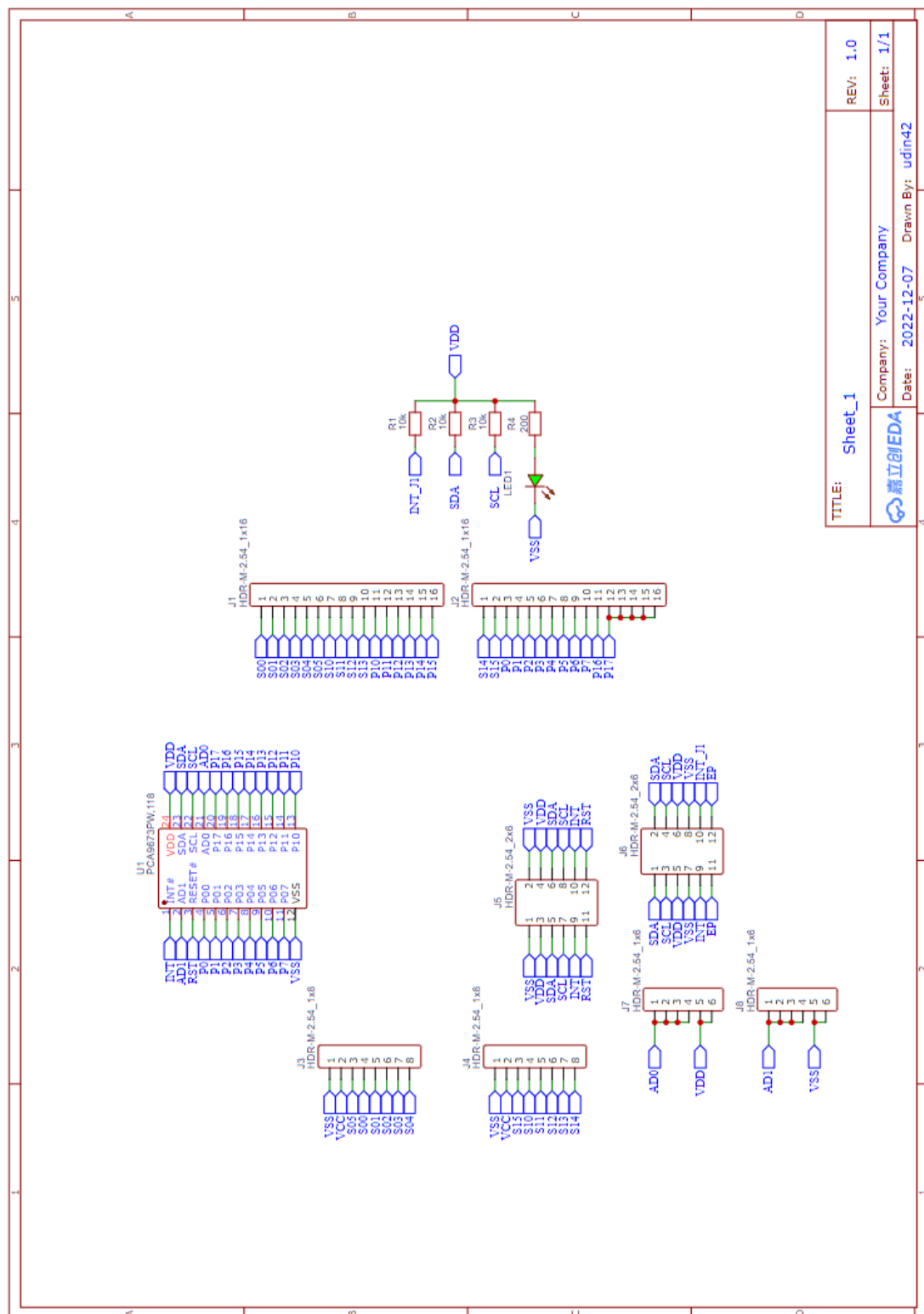




B. Electronic design: GPIO Expander PCA9555

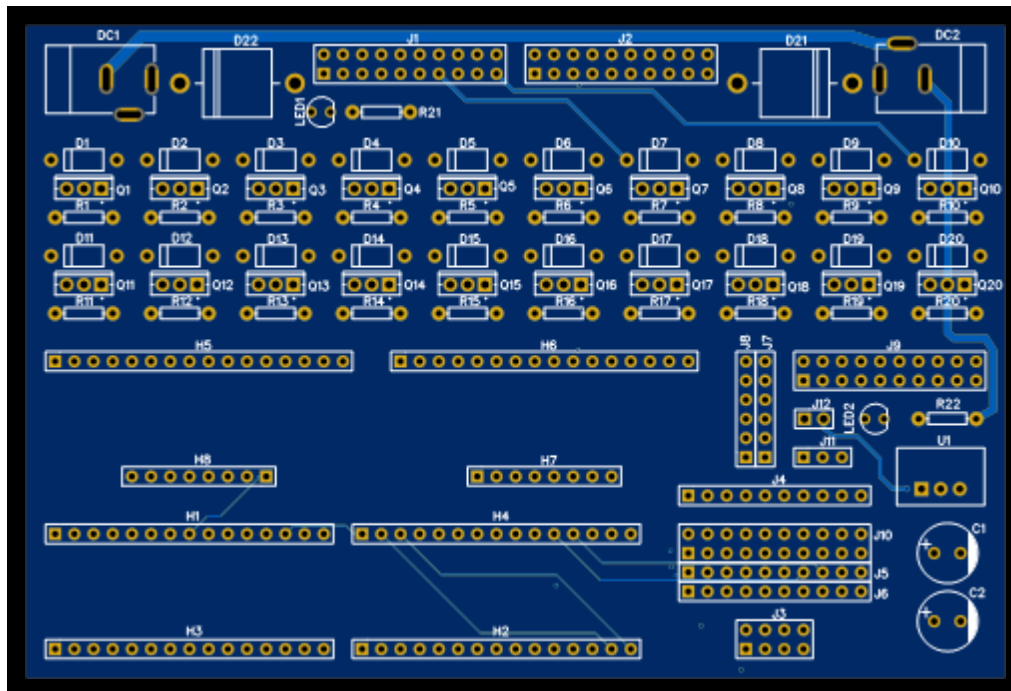


C. Electronic design: GPIO Expander PCA9672

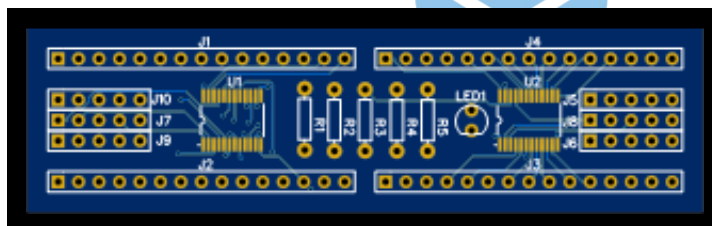


D. PCB layout

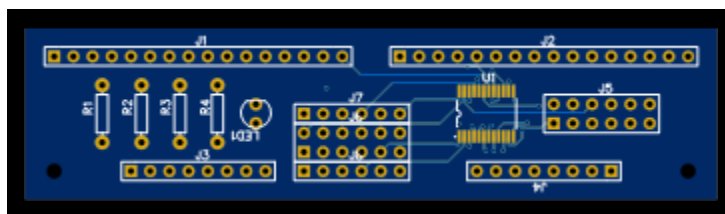
Electronic Driver



GPIO Expander PCA9555

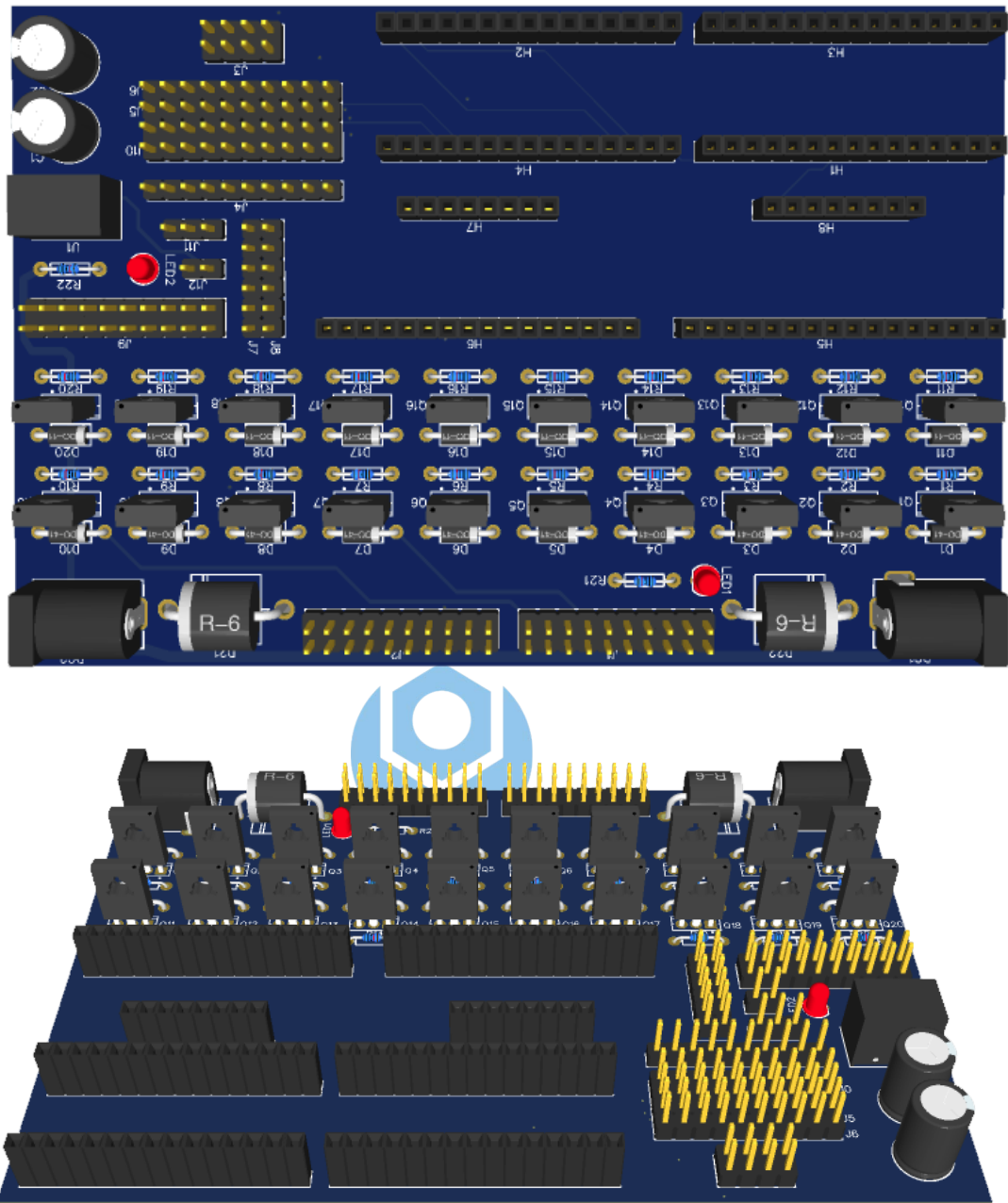


GPIO Expander PCA9672

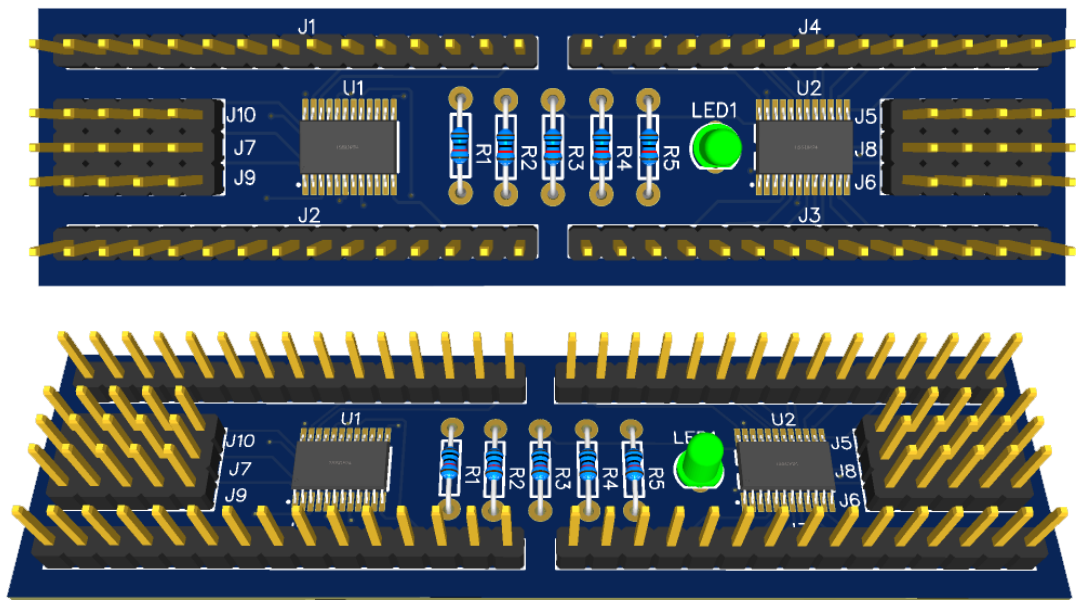


E. 3D view of PCB

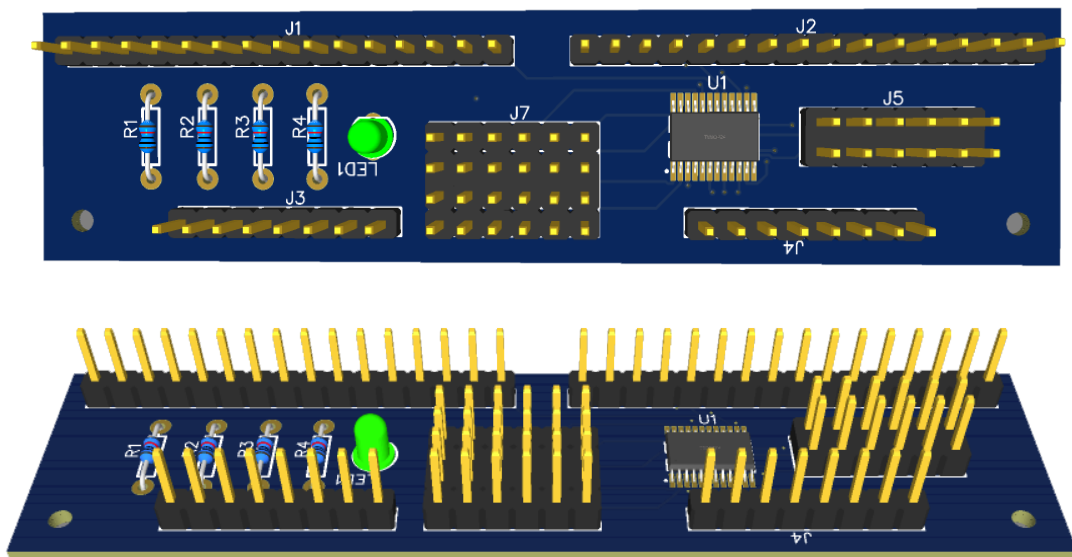
Electric Driver



GPIO Expander PCA 9555



GPIO Expander PCA9672



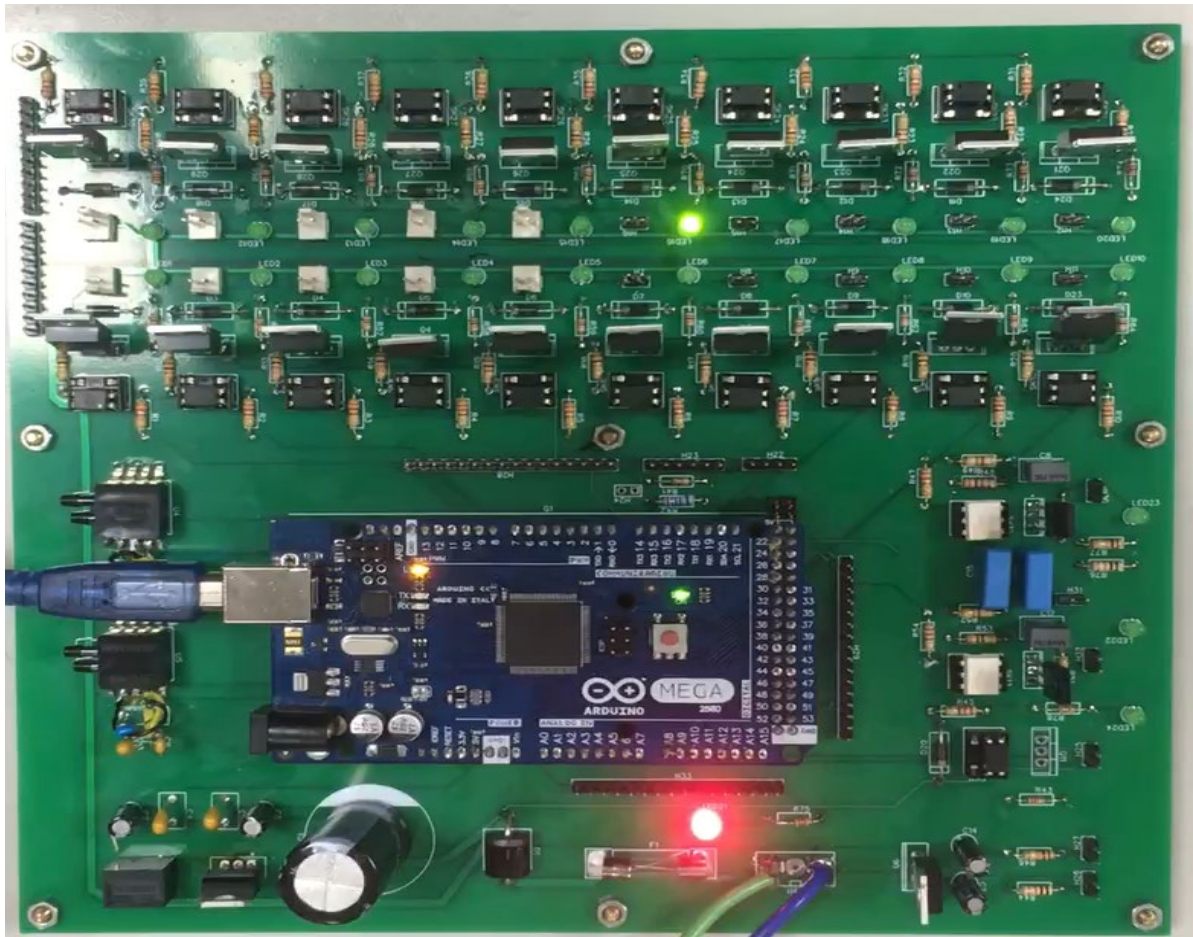
F. Table data on available space and required mass must be added to the mannequin to accurately simulate the real weight of a human

No.	Description	Initial (gram)	Target (gram)	Δ g	Δ Kg	Water volume measured (m3)	Required density (Kg/m3)
1	Foot (1 side)	167	1,170	1,003	1.00	0.0002	6,535.89
2	Leg (1 side)	486	2,800	2,314	2.31	0.002	1,424.11
3	Thigh (1 side)	993	7,165	6,172	6.17	0.003	2,372.20
4	Stomach	3,961	6,553	2,592	2.59	0.004	736.67
5	Hand (1 side)	372	3,400	3,028	3.03		
6	For arm (1 side)	474	4,140	3,666	3.67		
7	Chest	2,092	23,053	20,961	20.96	0.002	12,900.07
8	Head	800	4,555	3,755	3.76		
Total		9,345	2,836	43,491	43.49		

*The data were developed by adding water to check the available space inside the body segments of the mannequin.

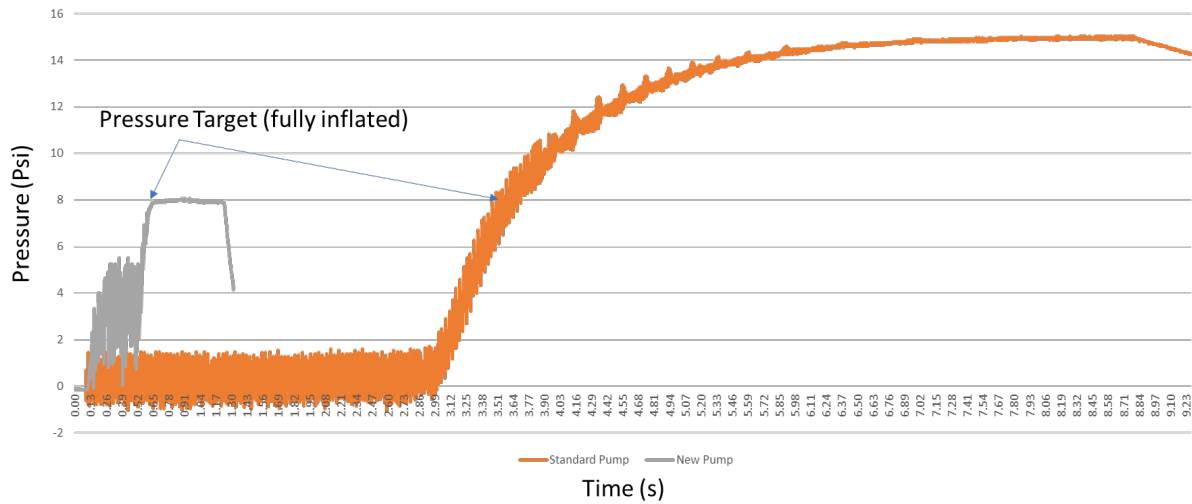


G. First PCB prototype



H. Pressure test on one dimensional air mattress

Pressure test on, speed of inflation when the single chamber air mattress gets direct air pressure from pump.



I. Multichambered air mattress, deflation area test (columns)



(a)



(b)



(c)



(d)



(e)



(f)

J. Multichambered air mattress, deflation area test (row)



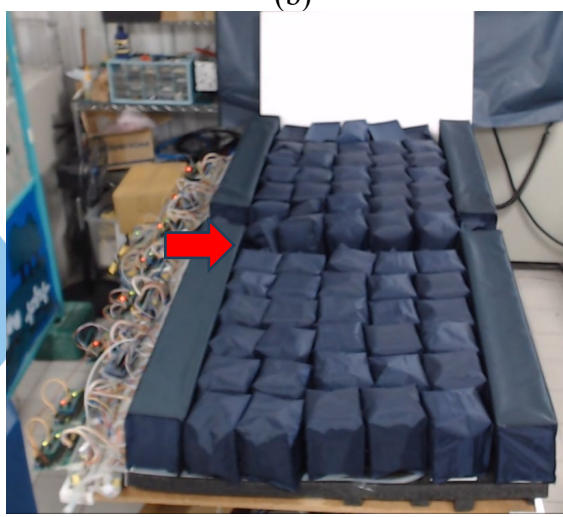
(a)



(b)



(c)



(d)



(e)



(f)