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Review

Bathing assistive devices and robots for the elderly

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ABSTRACT

The issue of aging population has become a severe problem that restricts global development. Thus, the development of bathing robots for the elderly is of great significance for the national strategy of actively addressing population aging. However, there is a lack of systematic review and analysis for the elderly bathing aids and robots, and the trend of the future development is also unclear. Therefore, by reviewing the relevant literature, this paper systematically analyzes the technical characteristics and usage scenarios of the lying, sitting and auxiliary posture, based on the bathing methods, bathing modes, and post bath care, which can clarify the current research status of bathing aids and robots for the elderly. Meanwhile, from the perspectives of the structural design, motion control and information intelligence, the key technologies and existing problems of bathing aids and robots are elaborated, and the relevant technical system is sorted out. Finally, based on the future of technological elderly care and the elderly bathing needs, the development trend of elderly bathing aids and robots is prospected, and the reference and suggestions for its research and development is provided, which has positive research significance.

1. Introduction

As the aging population intensifies, geriatric care has gradually become a severe issue that constrains the high-quality development of Chinese society. According to the projections of the United Nations, the proportion of people aged 65 and above is expected to increase from 10% in 2022 to 16% in 2050, when this age group will be twice the population of children under 5 years old and almost equal to the number of children under 12 years old. Furthermore, by 2050, the global proportion of people aged 65 and above is projected to further increase to 22% [1]. According to the United Nations criteria [2], a society is classified as "aged" when the proportion of its population aged 65 and above exceeds 7% and "super-aged" when it surpasses 14%. This threshold signifies that China has officially entered the "super-aged society" phase. Elderly individuals who have lost the ability to take care of themselves are referred to as "disabled elderly" or "elderly with disabilities". According to the international standards for analysis [2], the inability to perform 1–2 out of the six activities of daily living (ADLs), which include eating, dressing, getting in and out of bed, using the toilet, moving indoors, and bathing, is defined as "mild disability"; the inability to perform 3–4 activities is defined as "moderate disability"; and the inability to perform 5–6 activities is defined as "severe disability". Currently, the population of disabled and semi-disabled elderly in China has exceeded 40 million. Bathing, as a daily habit closely related to physical health, functional recovery, and personal dignity, has become a significant life challenge for the vast majority of the disabled elderly [3]. Efficiently, conveniently, and comfortably assisting the disabled elderly in bathing has become an increasingly challenging care issue in elderly care services at the current stage.

Bathing aids, as a branch of assistive devices for rehabilitation, are designed to utilize supportive equipment to help individuals with bathing disabilities complete the bathing process [4]. Based on the level of automation, prevailing bathing aids can be categorized into low-end, mid-range, and high-end assistive devices. Low-to mid-range bathing aids are primarily targeted at the early elderly population or those with mild disabilities, with representative products including simple bathing chairs, stools, and beds. High-end bathing aids, mainly for the severely disabled elderly, feature a higher level of intelligence and automation. Intelligent bathing aids refer to the integration of traditional bathing support devices with computer technology and motion control methods, thereby enhancing their level of automation and intelligence. As societal aging intensifies, the development of intelligent bathing

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aids holds significant importance for assisting the bathing of the disabled elderly and alleviating the pressures of elderly care [5].

In the 21st century, the robust advancement of technological avenues, including robotic networking and information technology, has offered novel perspectives and innovative solutions for addressing the challenges of elderly bathing. Bathing robots, as a branch of robotics, represent a type of intelligent bathing products that integrates structural design, control algorithms, and network informatization [6]. Present research on bathing robots mainly revolves around three aspects: pre-bath preparation, in-bath cleansing, and post-bath care. In terms of pre-bath preparation, the main challenge addressed is the difficulty elderly bedridden individuals face when entering the bath. Consequently, research on bathing robots principally focuses on the structural design of the robot body, with research focusing on two key aspects. Firstly, the research integrates ergonomic principles to optimize the spatial layout of the robot's bathing structure, enhancing the comfort of the bathing process. Secondly, the development of transferable and posture-adjustable devices aims to facilitate an unhindered bathing experience. Current achievements include the development of lifting transfer bathing devices, bathtub lifting mechanisms, transferable bathing beds, and transferable bathing chairs, among others [7–10]. In terms of in-bath cleansing, the development of bathing aids and robots focuses on the research of control systems. Prevailing functionalities that have been developed include soaking, massage, voice control, ultrasonic cleaning, and water temperature regulation [11–14] The development of a robot control system is at the core of its intelligence, and research in this area encompasses a wide range of topics. For instance, research in multi-sensor fusion [15], human posture estimation [16], force-position hybrid control in the washing process [17–19], human–robot interaction [20], and safety protection [21] are key directions in current bathing robot research. In the post-bath care aspect, bathing aids and robots are predominantly addressing issues such as body drying and the evaluation of cleaning effectiveness [22,23]. This stage involves the assessment and feedback of the bathing outcomes. Intelligent high-end bathing aids and robots are comprehensive products that cover the aforementioned three aspects of the bathing process. Therefore, they play a significant role in assisting the bathing of disabled elderly individuals and alleviating the pressure of elderly care. However, current overviews on elderly bathing aids and robots are not clear, and there is a lack of systematic literature review analysis, which is highly detrimental to the research and development of bathing aids and bathing robots.

Based on the aforementioned analysis, this paper synthesizes research literature from both domestic and international sources. Starting with the classification of existing bathing aids, it summarizes and analyzes the research progress in domestic and international bathing aids and robots. The paper categorizes the functional characteristics of bathing robots from different postures, such as sitting and lying down, and elaborates on the development history of bathing aids and robots. Furthermore, this paper discusses the key technologies and existing issues of bathing robots from the perspectives of structural design, motion control, and information intelligence, and organizes the technological system of elderly bathing aids and robots. Finally, it summarizes and analyzes future development trends, providing references and suggestions for the research of elderly bathing aids and bathing robots.

2. The current state of research on elderly bathing aids and robots

Bathing, as a fundamental need in daily life, has been an integral part of human production and living since the dawn of humanity. As depicted in Fig. 1, bathing utensils have a long history. Ancient bathing implements, such as bathtubs and washbasins, were chiefly designed for full reclining or semi-reclining bathing positions and did not possess auxiliary bathing functions. In modern society, the advancement of science and technology has given rise to a multitude of elderly bathing assistance products. With the market segmentation targeting the elderly population, bathing aids for the elderly can now be categorized into three types based on the degree of disability: reclining bathing aids for the severely disabled elderly, sitting bathing aids for the semi-disabled elderly, and assistive bathing aids for the healthy or mildly disabled elderly.

The evolutionary history of bathing aids can be broadly divided into three stages based on their level of intelligence: structured inclusive-type bathing aids, automated functional-type bathing aids, and intelligent-type bathing aids. The first stage in the development of bathing aids is the era of structured design, characterized by relatively simple functionality, such as basic bathing stools and chairs. In the 1960s, the Japanese Sakai Medical Corporation developed the first bathing robot powered by electricity in the world [26], which marked the beginning of product development for bathing aids targeting the disabled and semi-disabled elderly. During this phase, bathing aid products primarily focused on mechanical structural design, mainly addressing the bathing challenges for the disabled elderly through devices such as lever arms and wheelchairs, with relatively less research on the control of the bathing aids themselves. By the early 21st century, the development had entered the second phase. During this phase, with the rapid advancement of computer technology and the innovation of electrically driven devices, the automation level of the bathing aids has been significantly enhanced [27–29]. Therefore, many different types of bathing aids appeared, and more bathing functions such as soaking, massage, ultrasonic cleaning, and water temperature regulation were used. This has propelled the development of bathing aids in the direction of higher integration into bathing robots. Currently, bathing robots are advancing towards the third stage, namely, the stage of information intelligent aids. With deepening research into technologies such as biomaterials [30], information perception [31], and artificial intelligence [32], bathing aids and robots are now endowed not only with environmental perception and intelligent decision-making capabilities but also with the development philosophy of human-machine integration [33], data sharing [34], and multi-robot collaboration [35]. The required technologies are evolving from traditional engineering to interdisciplinary fields such as materials science, bionics, and psychology [36–39]. The research content is characterized by broader coverage, more pronounced interdisciplinarity, and cross-domain features. The overall research and development design is moving from a single-function or structured design towards an integrated approach of structure, control, and information. This represents the future research direction in the field. The development of this stage of bathing robots is of significant importance for alleviating the pressure on Chinese elderly care services, enhancing the well-being of the elderly, and improving the national level of happiness.

3. Technical features

3.1. Bathing robot

Based on the differences in the functions of different bathing robots, the technical features of the bathing aids and robots can be analyzed from two aspects: structural design and control system. Structurally, the bathing robot can be categorized into three types: reclining, sitting, and assistive robots. From the perspective

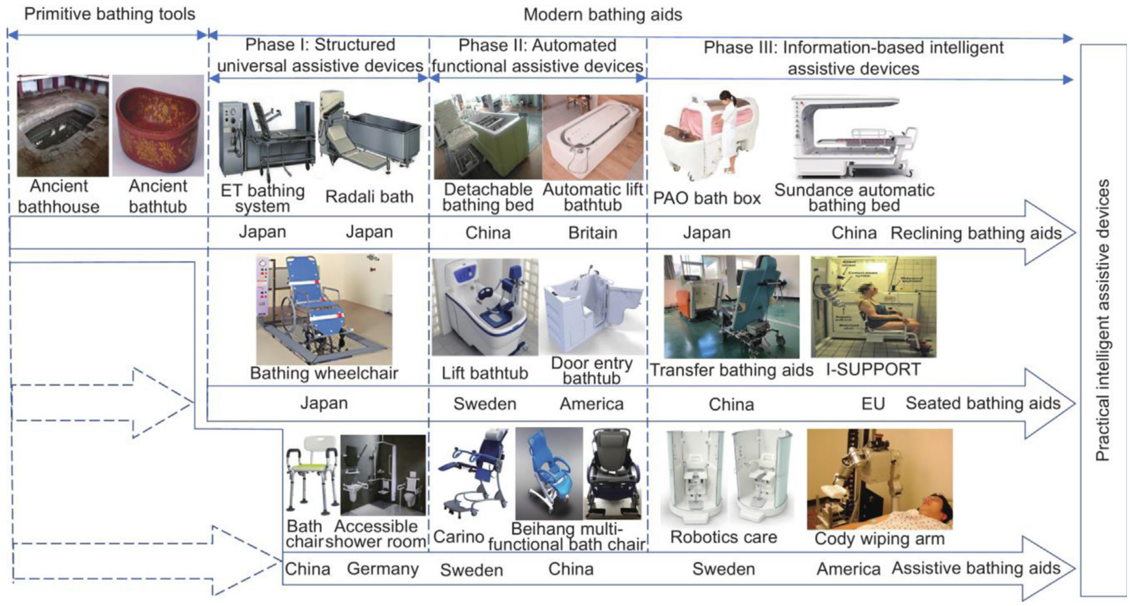

Fig. 1. The Evolutionary History of Bathing Aids and Bathing Robots. Ancient bathing bathhouse and Ancient bathub Copyright©, Baidu. ET Bathing System, Radali Bath, Bathing Wheelchair, PAO Bath Box Copyright©, Sakai Medical company. Detachable Bathing Bed, Copyright©, National Research Center for Rehabilitation Technical Aids (NRCRTA). Automatic Lift Bathtub, Copyright©, ABACUS Healthcare corporation. Sundance Automatic Bathing Bed, Copyright©2014, Sundance. Lift Bathtub, Copyright©, Arjo. Door Entry Bathtub, Copyright©, Google. Transfer Bathing Aids, Copyright©2020, ZJSTU. I-SUPPORT, Copyright©2017, IEEE. Bath Chair, Copyright©2010, Xinyue Health. Accessible Shower Room, Copyright©, Schtaf. Carino, Robotics Care Copyright©, Arjo. Beihang multi-functional bath chair [24,25], Copyright©2019, IEEE. Cody Wiping Arm, Copyright©2010, IEEE.

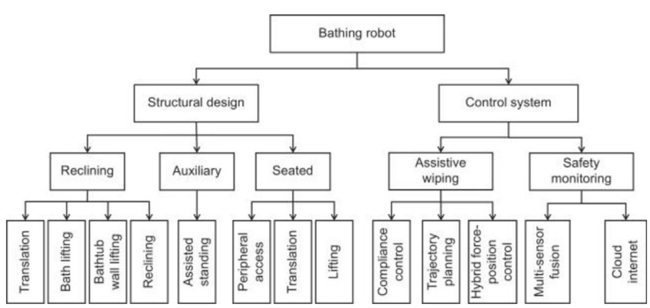

Fig. 2. Classification of Bathing Robots.

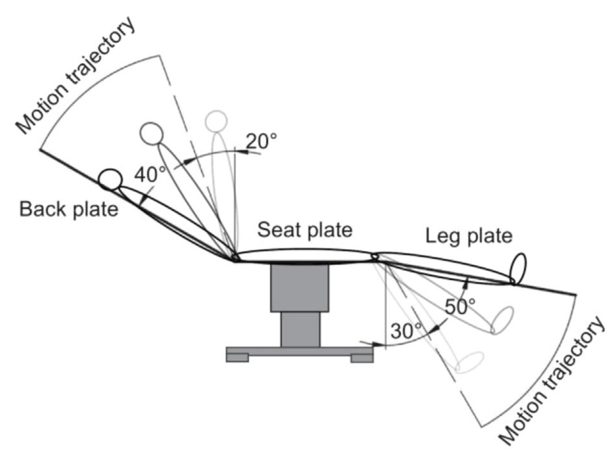

Fig. 3. Illustration of the reclining bathing bed movement.

of control system, this section mainly discusses the technologies required for auxiliary scrubbing and safety monitoring in bathing robots. Each category can be further divided according to different modes of operation, as illustrated in Fig. 2. These various categories will be systematically introduced in this section.

3.1.1. Reclining bathing aids and robots

The primary bathing postures are supine and sitting positions, with the most comfortable bathing posture for the human body generally being a 30° supine position with the back flat and legs bent at 10°, known as the reclining position, as shown in Fig. 3 [40]. The development of reclining bathing robots initially garnered the most attention from researchers. The working methods of reclining bathing aids and robots are primarily divided into two types: transfer-type and lifting-type. This section will mainly introduce the robots of these two types.

The mechanical structure of reclining transfer type includes the guide rail and the slider groove. The guide rail is typically under the bathing bed, while the slider groove is inside the bathtub. During operation, the transferable device is connected to the support board inside the bathtub by sliding along the guide rail into the slider groove, assisting the disabled elderly in entering and exiting the bath (Fig. 4a). For instance, as shown in Fig. 4b, the transfer-type shower robot developed by the Japanese OG Wellness company (OG) [41] effectively enhances the convenience and comfort of bathing. He et al. [42], applying ergonomic principles to their design, have developed a set of bathing aids composed of a bathing bed, bathing chair, and safety module. Experiments indicate that these bathing aids are simple to operate, relatively comprehensive in function, and can effectively reduce the burden on caregivers.

The reclining lifting-type bathing aids and robots mainly consist of two methods: bathtub inner groove lifting and bathtub wall lifting [28]. The former mechanism is illustrated in Fig. 4c, which operates through a scissor-lift mechanism placed beneath the bathtub for elevation (Fig. 4d). The latter mechanism is depicted in Fig. 4e, utilizing an electric actuator embedded within the cavity of bathtub wall for the lifting process (Fig. 4f). Wang et al. [43], addressing the issues of limited internal space and large lifting travel within the bathing tub, designed a lifting mechanism based on an electric actuator and conducted corresponding

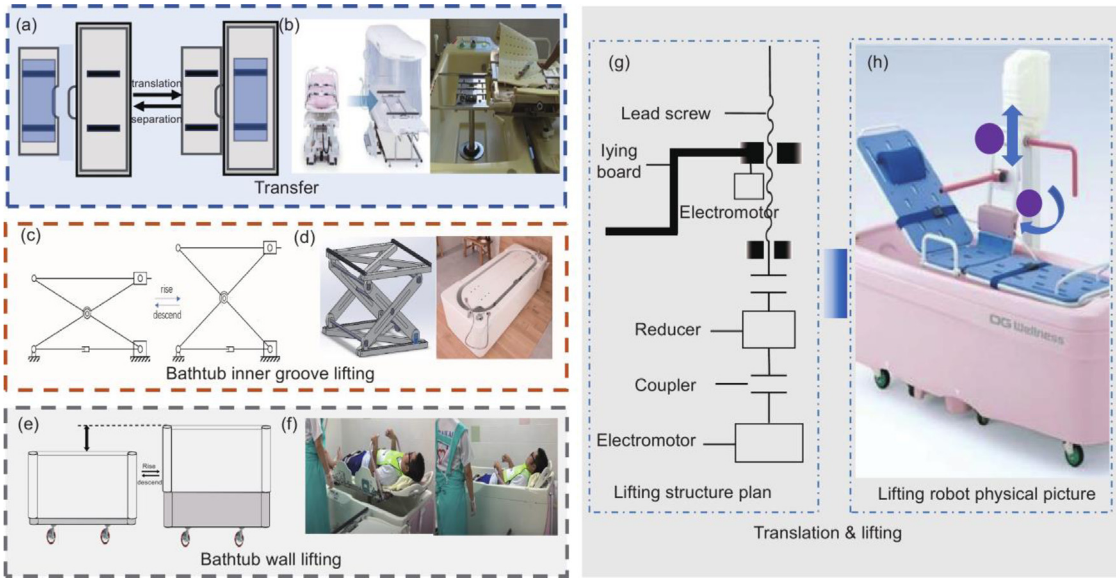

Fig. 4. Categories of Reclining Bathing Robots. (b) OG Sereno bathing robot, Copyright© 2013, OG Wellness company, Japan. (d) Lifting bathing robot, Copyright© 2018, IEEE. (f) Wall lifting bathing robot, Copyright©2019, heartful care. (h)OG Wellness bathing robot, Copyright©2013, OG Wellness company, Japan.

waterproofing and stress analyses. This scheme provides a reference for solving the bathing problems of individuals with severe disabilities. Lv et al. [44] designed a bath transfer product using a lift-style bathtub and sliding track from the perspective of human factors engineering. The bathing device utilizes an electric hydraulic scissor-lift mechanism to achieve elevation, and simultaneously incorporates a bathtub sealing structure capable of absorbing vibrations and positional deviations, thereby enhancing the waterproof performance. Zhou et al. [45], through their analysis of the bathing process for the elderly and persons with disabilities, have designed a dual-lift bathtub mechanism.

Subsequently, scholars have combined the transfer type with the lifting type, developing a transfer-lift composite bathing robot. The lifting principle involves the use of two motors to achieve the ascent, rotation, and descent of the bathing device, as shown in Fig. 4g [46]. When in use, the lift bed for elderly individuals is maneuvered alongside the bathtub. Once the lift bed is positioned above the bathtub, its height can be adjusted to assist the elderly in entering the bath, as exemplified by the OG Bath, as shown in Fig. 4 h. Guan et al. [47], addressing the limitations of bathing caregivers, have improved upon the existing wheeled transfer stretchers, devised a design scheme for a lifting transfer device for bathing paralyzed elderly individuals, and conducted simulation analysis. Wang [48] and Song et al. [49], through analysis of the psychological state and physical dimensions of individuals with severe disabilities, have designed streamlined lifting and rail transfer types of bathing aids that cater to the psychological and anthropometric needs of individuals with severe disabilities, and have conducted finite element analysis and human–computer interaction interface design.

The mathematical model of the internal scissor-lift mechanism of the bathtub is as follows: First, a mathematical model is constructed to analyze the motion characteristics of the four-bar lifting mechanism inside the bathtub, as shown in Fig. 5.

As shown in Fig. 5, the point A is defined as a fixed hinge support, L_1, L_2, and L_4 are the variables that L_2, L_4 represent the rod length of the four-bar mechanism and L_1 is the height of the mechanism during operation. L_3 is the fixed value that is the length of the support rod for the four-bar mechanism. Additionally, S_1, S_2, S_3 are respectively the lengths of each part of the four-bar mechanism support rod divided by hinge E. Therefore, the kinematic analysis of a conventional four-bar lifting mechanism, based on the closed vector relationship in Fig. 5, can be analyzed through vector equations to derive Equation (1):

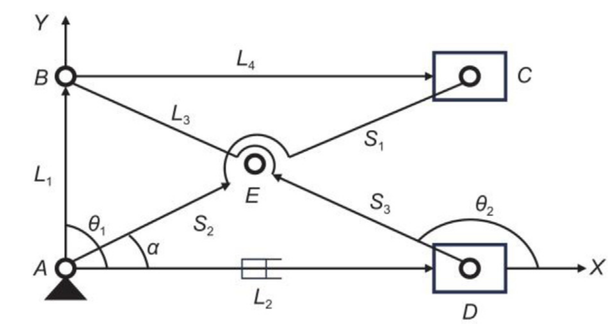

Fig. 5. Mathematical Model of the Bathtub Lifting Mechanism.

$$\vec{L}_1 = \vec{L}_2 + \vec{L}_3, \vec{S}_2 = \vec{L}_2 + \vec{S}_3 \tag{1}$$

When the vectors are projected onto the X-axis and Y-axis respectively, the following projection equations (2) are obtained:

$$\begin{cases} L_1 \cos\theta_1 = L_2 + L_3 \cos\theta_3 \\ L_1 \sin\theta_1 = L_3 \sin\theta_3 \\ S_2 \cos\alpha = L_2 + S_3 \cos\theta_3 \\ S_2 \sin\alpha = S_3 \cos\theta_3 \end{cases} \tag{2}$$

To obtain the first-order differential equation of the mechanism, differentiate with respect to time:

$$\begin{cases} V_B \cos\theta_1 = V_0 - L_3\omega_3 \sin\theta_3 \\ V_B \sin\theta_1 = L_3\omega_3 \cos\theta_3 \\ -S_2\omega_2 \sin\alpha = V_0 - S_3\omega_3 \sin\theta_3 \\ S_2\omega_2 \cos\alpha = S_3\omega_3 \sin\cos\theta_3 \end{cases} \tag{3}$$

where V_B represents the velocity of point B and V_0 represents the velocity of the slider D, which is also the speed of the electric actuator. ω_2 and ω_3 denote the angular velocities of bars AE and DE. Assuming V_0 is known, Eq. (3) can be transformed into matrix form (4):

$$\begin{bmatrix} \cos\theta_1 & L_3\sin\theta_3 & 0 \\ \sin\theta_1 & -L_3\cos\theta_3 & 0 \\ 0 & S_3\sin\theta_3 & -S_2\sin\alpha \\ 0 & -S_3\cos\theta_3 & S_2\cos\alpha \end{bmatrix} \begin{bmatrix} V_B \\ \omega_3 \\ \omega_2 \end{bmatrix} = \begin{bmatrix} V_0 \\ 0 \\ V_0 \\ 0 \end{bmatrix} \tag{4}$$

Finally, by recalculating the time, the acceleration analysis Eq. (5) of the mechanism is obtained:

$$\begin{bmatrix} \cos\theta_1 & L_3\sin\theta_3 & 0 \\ \sin\theta_1 & -L_3\sin\theta_3 & 0 \\ 0 & S_3\sin\theta_3 & -S_2\sin\alpha \\ 0 & -S_3\sin\theta_3 & S_2\sin\alpha \end{bmatrix} \begin{bmatrix} \alpha_B \\ \xi_3 \\ \xi_2 \end{bmatrix} = \begin{bmatrix} \alpha_0 - L_3\omega_3^2\cos\theta_3 \\ -L_3\omega_3^2\sin\theta_3 \\ \alpha_0 - S_3\omega_3^2\cos\theta_3 + S_3\omega_3^2\cos\alpha \\ S_2\omega_2^2\sin\alpha - S_3\omega_3^2\sin\theta_3 \end{bmatrix}. \tag{5}$$

3.1.2. Seated bathing aids and robots

Seated bathing robots are primarily designed for semi-disabled elderly individuals who have the ability to sit. In terms of structural design, the focus is on reducing the difficulty for the elderly to enter the bath. The main research content of this category of products includes peripheral access, seated lifting and seated transfer.

Peripheral access bathing robots mainly facilitate the bathing process for the elderly by opening a side of the bathtub, allowing them to enter. This design is particularly suitable for the elderly population with mild disabilities. Its bathing process typically includes the following steps: opening/lowering the bathtub door, the elderly entering the bathtub, and then closing/raising the bathtub door, as depicted in Fig. 6a. To accommodate the bathing needs of diverse elderly individuals and to reduce the difficulty of the elderly entering the bathtub, in the 1990s, the Japanese OG company designed and developed the Volante peripheral access bathtub [50]. This bathtub facilitates elderly individuals entering the bath in a seated position from the side through the mechanism of a lifting side wall. In recent years, the exploration of peripheral access bathing robots has chiefly focused on the comfort and safety aspects of the structural design. Sun et al. [51], from the perspective of industrial design, focused on the detailed exterior design of the edge-entry bathtub. Huang et al. [52] analyzed the bathing structure from the perspectives of elderly comfort and ergonomics. The methods improved by both have enhanced the bathing comfort of peripheral access bathing aids to a certain extent.

Seated lifting bathing aids and robots have improved the entry method of edge-entry bathing robots, mainly divided into integrated (Fig. 6b) and split-type (Fig. 6c) designs. In the integrated lifting product, the lifting mechanism is connected as one piece with the bathtub and is typically located at the rear of the bathtub. After the caregiver assists the elderly in moving to the lifting mechanism, the angle and height of the lifting chair or bed are adjusted to help the elderly enter the bath. In contrast, the lifting mechanism of the split-type product is designed to be separate from the bathtub. When assisting elderly individuals with disabilities or semi-disabilities to bathe, the lifting device carrying the elderly is first pushed in from the side towards the bathtub. Once the lifting device is positioned above the bathtub, the height is adjusted to assist the elderly in entering the bath. Numerous scholars have conducted in-depth research on this category of bathing robots. Hao et al. [53]designed a wheelchair bed device with lifting capabilities, ensuring the stability of the four-bar lifting mechanism during use and preventing interference to a certain extent. Chen et al. [24,25] designed a multifunctional bathing chair that integrates seat lifting and backrest inclination adjustment in response to the inconvenience faced by caregivers in cleaning. The entire seat is lifted by an electric actuator driving a parallelogram linkage mechanism, while the inclination of the backrest is adjusted by the forward and reverse rotation of the backrest motor, making cleaning care more convenient.

Compared to the aforementioned two categories of bathing products, seated transfer bathing aids and robots are more flexible and are more suitable for moderately and severely disabled elderly individuals. Its working principle involves integrating a movable chair with the bathtub body through guide rails, pushing the elderly individual into the bathtub to assist them in bathing, as shown in the workflow depicted in Fig. 6d. Ren et al. [54,55] has developed an autonomous navigation elderly bathing wheelchair based on the bathing characteristics of the elderly and leveraging technologies such as computer information, mechanical design, and automated control. The overall mechanical structure of the autonomous navigation elderly bathing wheelchair can be considered as being composed of two main parts: the bathing wheelchair body and the bathing wheelchair chassis. Wheelchair guide rails are set up on the bathing wheelchair chassis, and bathtub guide rails are installed on the bathtub to provide guidance for the docking of the bathing wheelchair with the bathtub, which plays a crucial role in ensuring their successful connection. The bathing chair achieves automatic docking with the designated bathtub by cruising autonomously along a pre-set magnetic strip, thereby reducing the labor intensity for caregivers and enhancing the safety of bathing.

3.1.3. Assistive bathing aids and robots

In contrast to the two major categories of bathing robots mentioned above, assistive bathing aids are primarily targeted at healthy elderly individuals or those with mild disabilities. These aids have a more singular functionality, mainly assisting the elderly with tasks such as standing and posture transition. At present, assistive bathing aids can be divided into passive and active types. Passive bathing aids are characterized by their lightweight design, simple structure, and low level of automation, with relatively singular functions such as assisting in posture transition and aiding in dressing and undressing. A representative product of this type is the multifunctional bathing chair, as shown in Fig. 7a. The multifunctional bathing chair facilitates the transition between sitting and lying positions for individuals, as well as assisting with leg lifting functions. Compared to the larger bathing equipment, the multifunctional bathing chair has a broader range of applications. Its lightweight, foldable, and compact features can better meet the bathing needs of the elderly at home and represent a future trend in the development of lightweight bathing equipment for home use. Active bathing aids have complex structures, larger sizes, and involve sophisticated control technologies. The research in this area predominantly focuses on assisting the elderly in standing, thereby better enabling elderly individuals with the capacity to stand to bathe independently. In this regard, Fu et al. [56], to help elderly individuals stand for extended periods during bathing, analyzed the human standing motion and designed an adjustable sit-to-stand assistive device that can accommodate differences in body size, reduce the weight borne by the body, and provide support for standing. Building upon this, Pei et al. [57] conducted an analysis of the exterior styling design of the bathing mechanism they developed, determined the appropriate dimensions for the

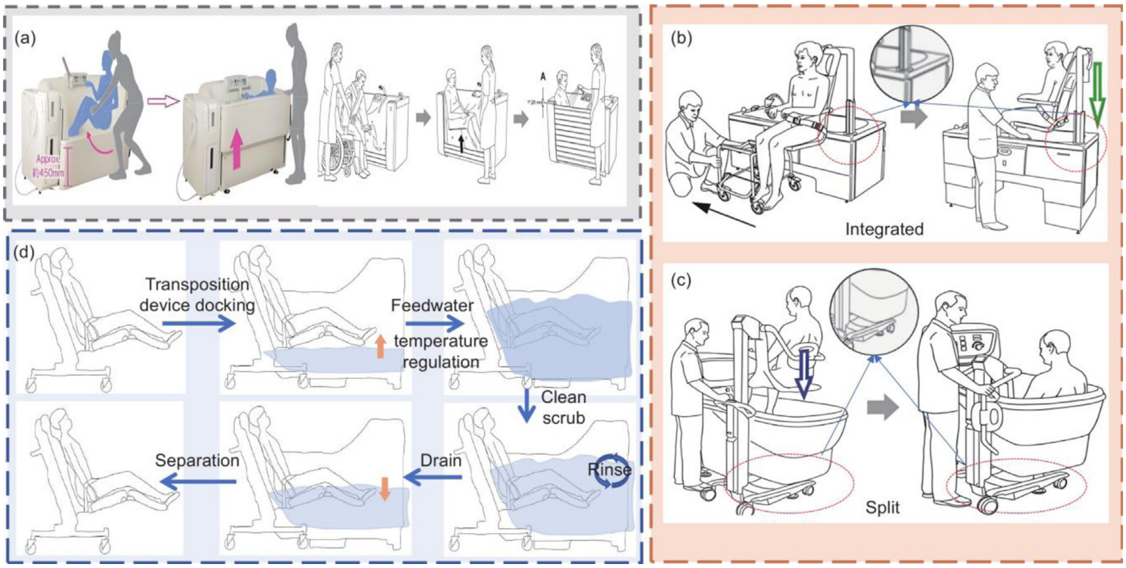

Fig. 6. Categories of Seated Bathing Robots. (a) OG Volante bathing robot, Copyright©2019, OG Wellness company, Japan. (b) Integrated seated bathing robot. (c) Split seated bathing robot Copyright© ARJO company, Sweden.

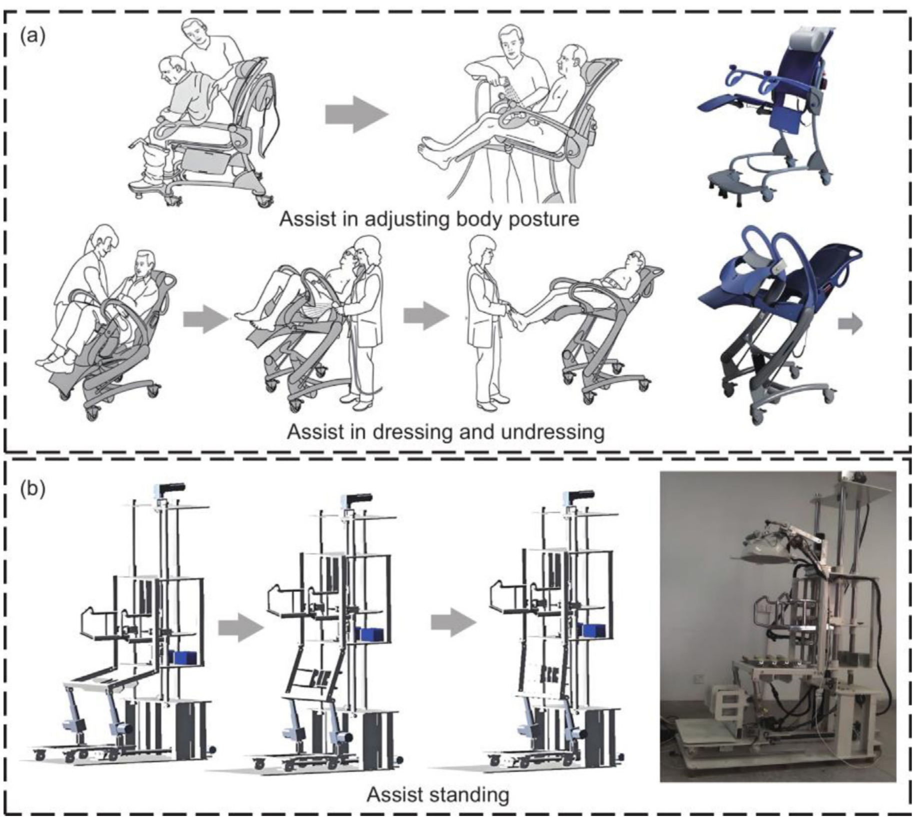

Fig. 7. Assistive Bathing Robot. (a) Carino and Carendo bathing robot, Copyright©, Arjo, Sweden. (b) Assist standing bathing robot [57], Copyright©2014, CMES.

relevant components, and thereby better met the needs of elderly bathing care and enhanced comfort during the bathing process, as shown in Fig. 7b. Furthermore, Yang et al. [58,59], through the analysis of the bathing needs of the elderly and frail populations, applied modular design concepts to develop a proactive assistive bathing robot capable of aiding users in standing/sitting and cleaning their heads and backs. This robot can actively assist users throughout the entire bathing process, effectively reducing the caregiving pressure on families and enhancing the quality of life for the elderly.

3.1.4. Structural summary of bathing aids and robots

Reclining bathing aids and robots are currently the most widely used types of bathing aids for the disabled elderly and are also the subject of extensive research. However, for the severely disabled elderly, an autonomous bathing mode that is convenient, safe, and effective has not yet been established. There are still issues such as large size, low flexibility and convenience, and insufficient personalized bathing modes. Further integration of technologies such as human-machine compatibility, structure, control, and information platforms to enhance the autonomy of bathing robots will be one of the key focuses in this field. For seated bathing aids and robots, there is not much variation in design. However, the integration of networked information technology, through autonomous navigation, personalized bathing recommendations, and multimodal human–robot interactive bathing, will be the future research trend for seated bathing aids and robots. Assistive bathing aids are primarily designed for specific aspects of the bathing process, such as aiding in standing, dressing, and wiping. The structural design varies in complexity depending on the function, providing feasible solutions for elderly individuals with varying degrees of disability during bathing. With the advancement of intelligent technology, the application of modular design concepts to integrate functional bathing aids with bathing beds, chairs, and other movable devices through artificial intelligence, the internet, and other technologies will further balance the convenience and efficiency of bathing equipment. This approach will be one of the hot directions for future research.

3.2. Control system

Different bathing stages, such as pre-bathing preparation, in-bath cleaning, and post-bath care, have different control technology issues. During the pre-bathing preparation stage, the focus is on addressing the challenges elderly face in entering the bath. Research in this phase mainly pertains to the structural design of the bathing robot. The control technologies in this stage primarily ensure the proper functioning of these structures, laying the hardware foundation for subsequent cleaning. And post-bath care includes technologies such as drying and disinfection, and the control technologies in this phase focus on evaluating the bathing effect. While the most critical part of the bathing robot is the safe and efficiency, which determines bathing comfort and cleanliness. The control technologies involved include multi-sensor fusion, compliance control, and hybrid force-position control, as depicted in Fig. 8.

In Fig. 8, the crux of control technology in the realm of bathing robots is the exploration of the spatial relationship between the human body and the robot. This exploration begins with the acquisition of anthropomorphic and robotic posture data through multi-sensor fusion, which involves capturing 3D human posture, formulating cleansing trajectories, and monitoring physiological indicators. This sensory information is then seamlessly integrated into a hybrid control framework that encompasses both force and compliant control strategies. The culmination of this process is the uploading of data to a cloud platform for centralized information management, thereby enabling remote control capabilities. The current trajectory of research in bathing robot control is primarily directed towards the refinement of assistive wiping mechanisms using robotic arms and the advancement of safety monitoring systems integrated with bathing aids. These represent the core challenges of bathing robot control technology. Therefore, this paper focuses on analyzing the control technologies of assistive wiping and safety monitoring.

3.2.1. Assistive wiping

The scrubbing functionality is a hallmark of the bathing experience, signifying both the level of comfort and the degree of cleanliness attained. The robotic-assisted bathing system has two key research areas that include studying the mechanical structure of scrubbing devices and developing scrubbing control algorithms. The former is mainly directed towards the creation of scrubbing devices that adeptly address the purification of the human epidermis. Hou et al. [60] have designed a proactive home bathroom back-rubbing robot by simulating the actions of rubbing and massaging the back with human hands. Through analyzing the force curves and optimal motion trajectory curves of the palm during back-rubbing, they aimed to address health and hygiene concerns. Shang et al. [61] have designed an automatic back-scrubbing device that utilizes data from bathers and an expert system control algorithm to determine the optimal scrubbing speed and motion trajectory. This device utilizes an expert system control algorithm, specifically the inference engine of the expert system, to determine the scrubbing speed and regulate the motion speed of the actuating mechanism for back-scrubbing. In this way, it balances the efficiency of scrubbing with the comfort of bathing. Li et al. [62] have designed a seat-based scrubbing system, which is built upon an assistive standing bathing robot. This system allows the elderly to scrub their back and lower legs comfortably while seated, and to effectively wipe their buttocks while standing. Chen et al. [63] have developed an automatic back-scrubbing robot by analyzing and researching the functions and techniques of back-scrubbing. For the control aspect, a Programmable Logic Controller (PLC) was implemented, and a prototype was ultimately constructed to conduct a feasibility study.

In terms of scrubbing control algorithm research, the team of Chih-Hung King in the United States has developed a dual 7-DOF arm assistive wiping robot that was named "Cody" [64], as shown in Fig. 9. This robotic system is equipped with an intricate mechanical arm and wiping end effector design. Through kinematic and dynamic analysis, it employs the Equilibrium Point Control (EPC) method from impedance control to generate the motion trajectory of the mechanical arm. During the cleaning process, the robot initially utilizes a laser rangefinder and camera to scan the curvature of the human body and capture point clouds. It then generates an OpenCV image at the end of the arc and overlays it with the point cloud. Subsequently, it executes a cleaning motion algorithm, following the generated motion trajectory to repetitively move the end-effector to perform the cleaning action. Finally, the robot lifts its end-effector from the body of the subject, completing the entire wiping procedure.

Additionally, the I-SUPPORT bathing robot [65] is capable of supporting and enhancing the mobility, manipulation, and force application abilities of elderly individuals, assisting them in completing the entire showering task sequence. At the control level, the robot integrates technologies such as environmental perception, motion planning, and human–robot interaction [66]. It uses point cloud data received from depth sensors as input and performs body part recognition and segmentation based on user perception algorithms and deep learning techniques [67], calculating and modifying the end-effector motion trajectory of the robot online [68]. Specifically, the robot features two modes of human–robot interaction: natural tactile interaction and remote sensing teleoperation. The former guides the soft robot to the appropriate position through direct physical interaction, performing gravity and friction compensation. The latter employs a remote control to direct the soft robotic arm to execute fine, smooth movements. To fully accommodate user needs, the I-SUPPORT robot has been designed and developed with cognitive learning algorithms for real-time gesture and intent recognition, selecting the most likely motion intent based on control primitives.

The I-SUPPORT robotic system, as shown in Fig. 10, employs sophisticated user perception algorithms to process point cloud data acquired from depth sensors, yielding a depth image as an output. Subsequent image transformations and computations are conducted to ascertain the 6D reference pose of robotic system. The specific implementation steps of the aforementioned functionalities are delineated as follows:

Firstly, calculate the minimum and maximum coordinates of the effective pixels along the image axis to define the 2D range of the body part on the image plane. **Secondly,** convert the result from the 2D "canonical" space to the image space by performing

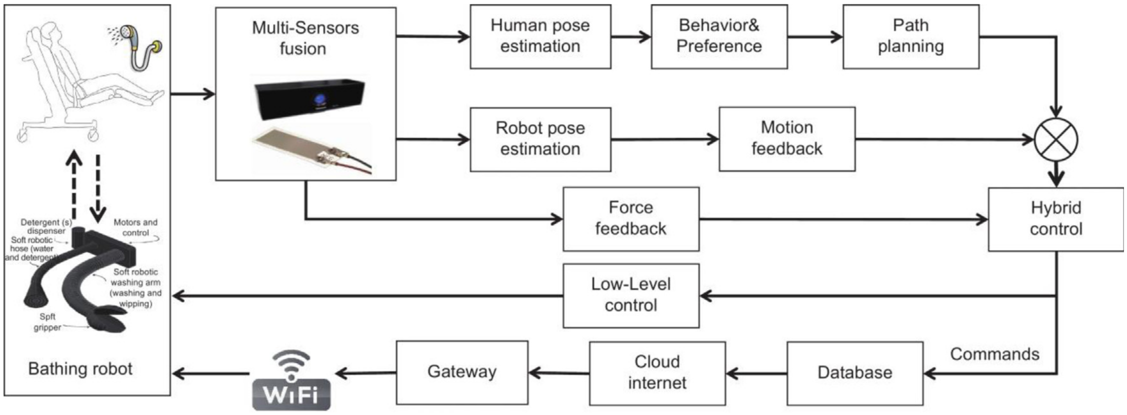

Fig. 8. Overall Architecture Diagram of the Bathing Robot Control System. Camera and pressure sensor, Copyright©, Baidu. Bathing robot arm, Copyright©2016, IEEE.

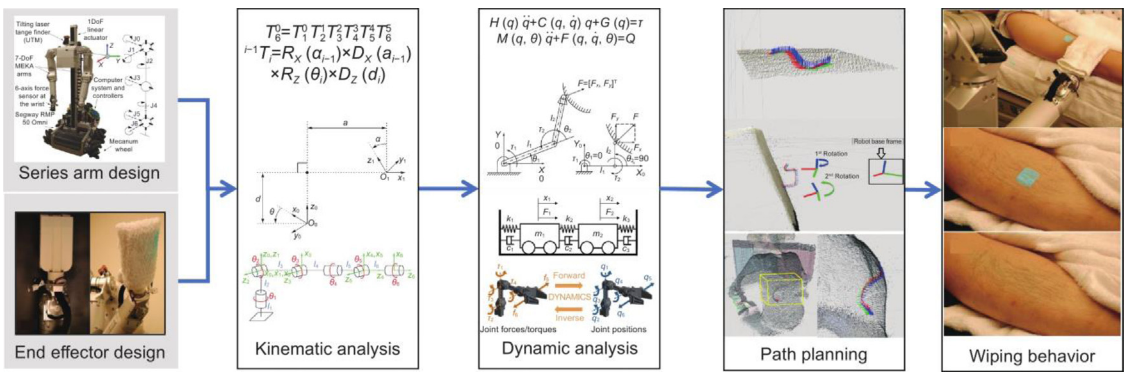

Fig. 9. Wiping Process of the Cody Robot Wiping robot "Cody" [64], Copyright©2010, IEEE. Wiping path planning, Copyright©2017, IEEE. Others, Copyright©, Baidu.

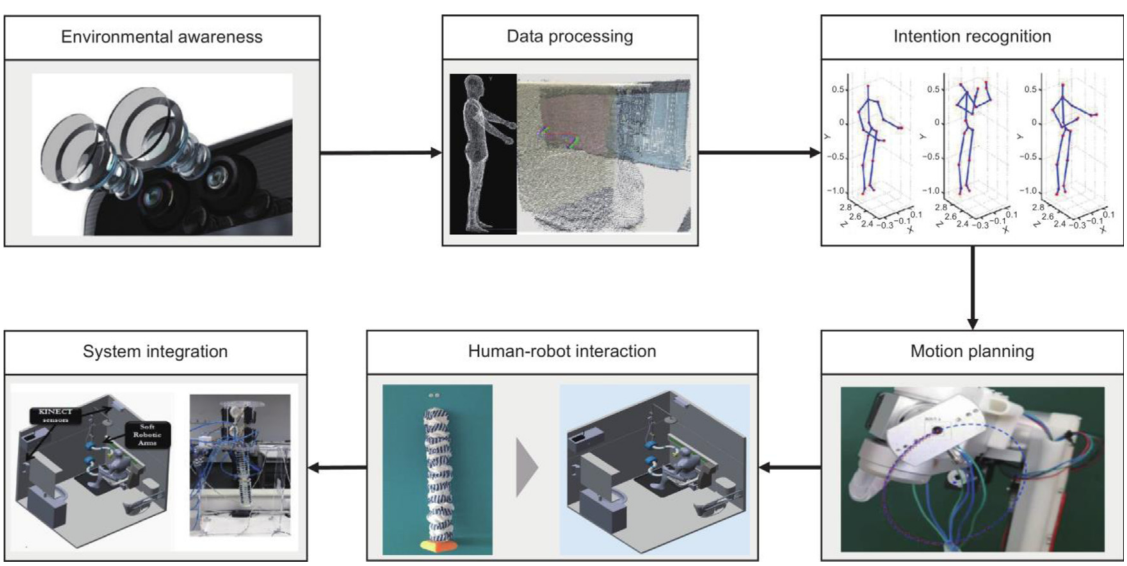

Fig. 10. I-SUPPORT Robot System Working Framework. Wiping robot "Cody", Copyright©2010, IEEE. Wiping path planning, Copyright©2017, IEEE. Others, Copyright©, Baidu.

anisotropic scaling. **Finally,** transform a set of moving points in the image space to a 3D task space, calculate the mean of these points, and perform eigenvalue decomposition on their covariance matrix.

Furthermore, to enhance the human feature recognition capabilities of bath scrubbing, Zhuang et al. [69]. used deep learning methodologies for the semantic segmentation of human features in a water fog environment. The experimental results show that the algorithm adeptly identifies feature information for 3D human models of diverse body sizes, which possessed significant engineering application value. Zhai et al. [70] proposed a constant force self-tuning control based on GA-Fuzzy-PID algorithm to address the issue of constant force control for the bathing assistance robot's end-effector during direct contact with human skin. Meng

Table 1
The classification of sensor functions in safety monitoring systems.

Sensor	Sensor category	Function	Reference
Physical information sensor	Ultrasonic sensor	Distance detection	Reference [64–66]
	Camera, Radar	3D information detection	Reference [16,63,64]
	Temperature sensor	Monitor water temperature	Reference [12,73–75]
	Sound sensor	Voice control	Reference [13,14,69–71]
Physiological information sensor	Humidity sensor	Monitor humidity	Reference [73,76,77]
	Heart rate sensor	Monitor heart rate	Reference [73,76]
	Temperature sensor	Monitor body temperature	Reference [22,23,73,77]

et al. [71]. applied the dynamic path planning algorithm based on 3D cloud recognition to recognize and track the dynamical human back, and path planning on it. To address the accurately sensing the human body in a contact-rich manipulation task of robot-assisted bed bathing, Gu et al. [72]. proposed a multimodal sensing approach that perceives the 3D contour of body parts using the visual modality while capturing local contact details using the tactile modality. The experimental results indicated that this is a promising approach for assistive bed bathing robots to accurately sense the human body and perform safe interaction.

With a higher level of automation, the bathing system integrates a range of sophisticated algorithms and technologies, essentially covering all steps of the bathing process, thereby ensuring the completeness and comfort of the bathing experience.

3.2.2. Bathing safety monitoring technology

Bathing safety monitoring is a necessary condition to ensure the safety of bathing robot system, which primarily uses the physiological sensors to monitor the physical parameters of the elderly and utilizes the physical sensors to warn the working status of the robot. The specific classification and functions are shown in Table 1. Tao et al. [73,74], building upon the foundation of the transfer-type bathing aid, have conducted extensive research on its control system. This research has led to the integration of bubble bathing capabilities, voice control functionalities, and a robust safety protection and warning mechanism. These enhancements are aimed at significantly improving the safety of elderly individuals during bathing. Tong et al. [75], in response to the actual bathing needs of the disabled elderly, have developed a voice recognition system with a small vocabulary suitable for use in the noisy bathroom environment to assist with bathing. Chen et al. have developed a modular bathing robot [76], which employs a modular functional design approach. Different modules are designed for various body parts such as the head, back, and limbs. The control of each module is independent, and the coordination among modules effectively addresses the bathing needs of elderly individuals living alone, offering significant practical and promotional value. However, the network integration of robot is insufficient, and there is room for improvement in the real-time interactivity and autonomy of its multimodal interactions. Liu et al. [77] have combined the reclining transfer method with a shower approach to design an automatic bathing nursing robot with a "C"-shaped bathing bed structure. They proposed an evaluation method for the cleanliness effect of bathing, which combines a hypothesis testing method based on the skin surface grease content with the ANOSIM method. Additionally, the robot incorporates functions such as body surface monitoring and post-bath disinfection, further meeting the personalized bathing and nursing needs of the disabled elderly (Fig. 11). Xu et al. [78,79] have developed a control system for an intelligent assistive bathing device for individuals with severe disabilities, featuring water temperature control and hydrotherapy functions. The system utilizes a proportional–integral (PI) control algorithm to achieve water temperature regulation and health monitoring capabilities. Zhang et al. [80] designed a bath accessory with automatic dehumidification and deodorization, drying and air supply and humanized interaction from the aspects of software and hardware technology based on the embedded foundation. Liu et al. [81], with the objective of enhancing safety during bathing for the elderly, have developed a system that utilizes real-time monitoring of temperature, humidity, and photoelectric signals to detect potential falls. By promptly identifying any such incidents, this system ensures the safety of elderly individuals while they are bathing, providing them with a more secure and worry-free bathing experience.

4. The existing issues with elderly bathing aids and robots

Bathing, as an indispensable part of the daily life of disabled elderly individuals, represents a significant issue within geriatric care. Although researchers both domestically and internationally have developed corresponding bathing products to meet the needs of different elderly populations, taking into account the mechanical structure, motion control, information perception, and psychological aspects of the elderly, several issues persist.

4.1. The relatively simple structural design leads to insufficient human-machine compatibility

At present, while there are a multitude of structural designs for bathing robots, their fit with the physical form of elderly still needs significant enhancement, which hinders their broad dissemination. The primary reasons for this are the lack of structural delicacy and the large space they occupy. Current intelligent bathing aids also generally suffer from a lack of delicacy in design, leading to issues with space consumption, making it challenging to utilize them extensively in domestic settings. Furthermore, the structural design lacks research in ergonomics, biomechanics, and the psychological characteristics of the elderly. Prevailing structural designs of bathing robots predominantly consider only the analysis of rigid body motion under ideal conditions, failing to conduct motion analysis from multiple aspects such as physical structure, skin condition, and psychological state. This oversight can potentially increase the risks associated with improper postures during bathing, thereby creating safety hazards for elderly users. Additionally, there is a deficiency in material research, with a lack of holistic studies integrating material structure. Material research should encompass aspects such as anti-slip properties, skin friendliness, waterproofing, and human-machine compatibility. The present development of bathing aids primarily focuses on the design of rigid mechanical structures. However, given that human skin is a flexible soft tissue structure, the designed products often fall short in terms of comfort, skin affinity, and user experience. There is a lack of research in areas such as biomimicry, material science, and the design of structures that effectively couple rigid and flexible elements.

4.2. Insufficient study of multimodal autonomous bathing collaborative control methods

Currently, most bathing robots require the involvement of caregivers to complete the bathing process, and there is still a

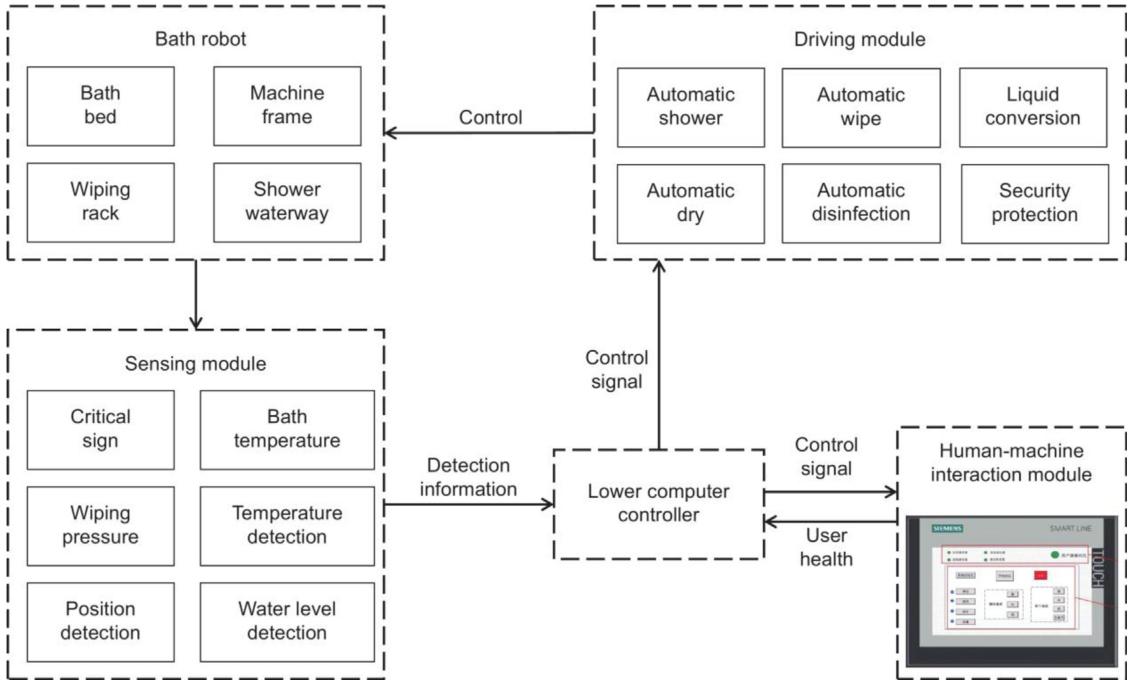

Fig. 11. System Composition of the All-round Cleaning Bath Assistance Robot. Human-machine interaction module [73], Copyright©2021, ZJU.

gap in achieving fully autonomous bathing. The specific reasons are as follows. First, the functionality is relatively singular, and multimodal collaborative control is weak. Whether it is a seated bathing robot or a reclining bathing robot, there are deficiencies in the functions implemented. Most products either focus on the method of entering the bath or concentrate on the bathing process itself. In-depth research on the collaborative control of various bathing modes, such as dressing and undressing before and after bathing, multi-posture transitions during bathing, and autonomous scrubbing, has not been conducted. There is a need for further strengthening in the integration of multi-source information and control decision-making. Second, the safety of the control system is insufficient, and the ease of operation is poor. In the field of intelligent bathing aid products, especially in the design research, the ergonomic design and mechanical structure design are often considered separately, which usually focuses on the implementation of the mechanical structure. To address these challenges, advanced control approaches, such as reinforcement learning for adaptive control and multi-sensor fusion for real-time decision-making, are critical. Future efforts should integrate ergonomic and mechanical design, ensuring user safety and ease of operation while leveraging artificial intelligence to optimize collaborative control across the bathing workflow.

4.3. Lack of comprehensive and systematic research on information integration management technology

Despite the development of numerous bathing products both domestically and internationally, the focus has primarily been on improving specific functions. This has led to an underutilization of data regarding the elderly with disabilities, failing to meet their personalized and comprehensive bathing needs. The specific reasons are as follows: First, there are certain difficulties in collecting body data from the elderly with disabilities. The present channels for obtaining physical information on the disabled and semi-disabled elderly are predominantly hospitals and nursing homes. However, there is often a lag in data transmission between medical institutions and corporate R&D, leading to distorted data analysis. Second, there is a lack of systematic coordination at the technical level, and human–computer interaction technology is immature. Most current products have only achieved simple bathing model training and have not established a comprehensive bathing model in aspects such as autonomous scrubbing, posture transition, vital sign monitoring, and human–computer interaction.

5. Trends in the development of bathing aids and robots for the elderly

To actively address the issue of population aging, intelligent bathing aids and robots have emerged as viable solutions to enhance bathing efficiency and alleviate the pressure of caregiving. In the present stage, elderly bathing robots have achieved some success in methods such as intelligence and automation, but there is still a gap before they can be widely applied in practice. The future development direction of bathing robots will focus on aspects such as structural design, control planning, and information integration management.

5.1. Material-structure-control integration

Bathing aids and robots are targeted at the elderly population with disabilities and semi-disabilities. The atrophy of the sebaceous glands and the reduction of elastic tissue in the elderly lead to decreased secretion of surface oils on the skin, loss of luster, relaxation with the appearance of wrinkles, and increased fragility of blood vessels. Furthermore, the elderly often experience a decline in physical function and a reduction in responsiveness, leading to a dulled reaction to external stimuli. This results in a weakened defense against environmental factors and an increased sensitivity, making them more susceptible to injury. The structural design should take into full consideration the physiological functions, skin tissue, and psychological state of the elderly, integrating principles of ergonomics, biomechanics, and the psychological characteristics of the elderly. It should evolve towards an integrated approach that encompasses materials, structure, and control systems.

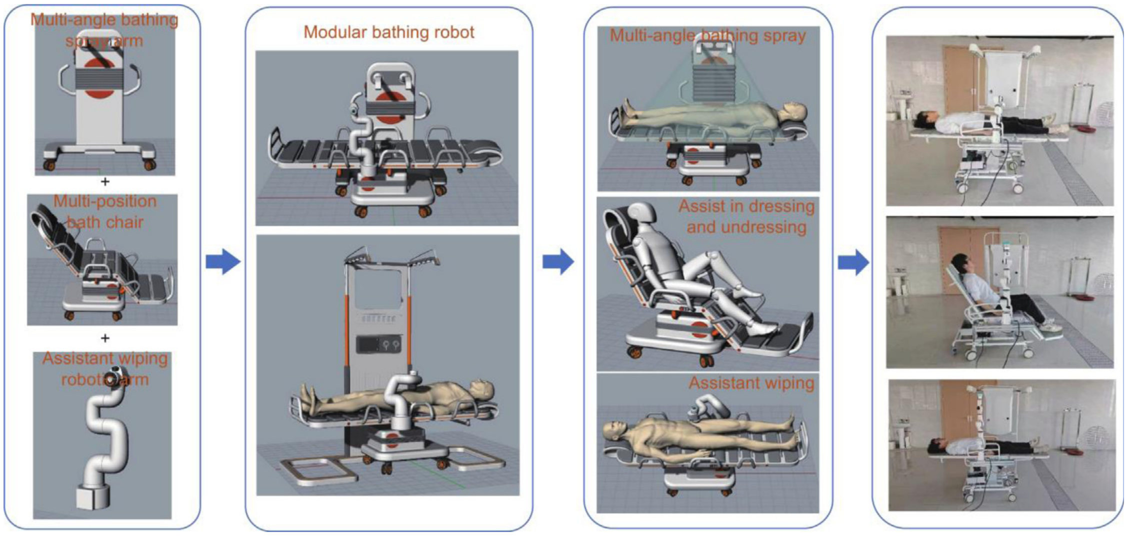

Fig. 12. Modular bathing robot.

5.2. Multimodal information fusion and compliant control

The control system of bathing aids and robots is the core of the entire device, involving the processing of multimodal complex information such as physiological signs, body posture, psychological responses, and safety protection during a complete bathing process for the elderly. To address the current challenges faced by disabled and partially disabled elderly individuals during bathing, the control system must be logically designed and developed, grounded in a thorough understanding of their physiological characteristics, bathing routines, and nursing requirements. This necessitates the integration of a multi-mode and multi-posture smooth transition mechanism within the architecture of bathing control system, thereby facilitating safe and comfortable bathing experiences across diverse postures and body parts. Furthermore, leveraging multi-sensor fusion technology to accurately detect the position of human body and the posture of robot, and integrating this with physiological information and feedback on the posture of mechanism, represents a trend in future research. This approach aims to transition from traditional rigid human–robot interaction to flexible, wearable human–robot interaction.

5.3. Cloud-edge-device intelligent information management and optimization

Currently, the development of bathing aids and robots is primarily focused on the functional implementation of individual robots. However, in response to the significant pressures of elderly care, the future trend will involve the use of multiple robots working in coordination to further enhance the efficiency of elderly care. This approach raises technical issues related to multi-robot communication, scheduling, decision-making, and the associated control difficulties. Although the practical issues such as the floor space required for deployment and the cost of implementation cannot be ignored, it can provide new ideas for balancing the efficiency and cost of elderly bathing care. In addition, to address this issue, our research group has developed a modular bathing robot, dividing it into three modules: a robotic arm with scrubbing functionality, a bathing chair with adjustable multi-posture capabilities, and a spray arm with an adjustable water angle, as shown in Fig. 12. This modular design aims to better meet the needs of different usage scenarios, such as homes and elderly care institutions, while providing new ideas for future multi-robot collaborative bathing systems.

By leveraging big data and cloud computing technologies, an information integration management model based on cloud platforms can form an integrated cloud–edge-device bathing model. This approach aims to provide comprehensive and personalized bathing services for the elderly. In cloud–edge-device integrated technology, the edge handles data collection and management by healthcare professionals, the cloud focuses on designing big data algorithmic models, and the devices rely on active user participation and cooperation. Consequently, it is essential for researchers to approach it from multifaceted and multidimensional technical perspectives. Moreover, ensuring data security and privacy, particularly for elderly users, is indeed a critical consideration, and this point will be addressed with proposed measures such as data encryption and secure access protocols.

By utilizing artificial intelligence technology, the online learning techniques for the daily bathing patterns of the elderly can be established, which collects each individual's bathing data, analyzes the bathing preferences of different individuals or groups This will provide a rapid recommendation scheme for the elderly experiencing bathing for the first time and continuously optimize personal bathing plans.

5.4. Potential ethical considerations

Ethical issues play a critical role in the future development of bathing robots. One primary concern is privacy related to data collection in robotic systems. Bathing robots often rely on sensors and connected technologies to gather users' physiological and behavioral data. Without robust safeguards, this data could be vulnerable to breaches or misuse. To address this, developers must implement stringent data protection measures, including encryption, access controls, and compliance with privacy regulations, to ensure the security and confidentiality of user information.

Another key consideration is the autonomy and informed consent of elderly users when using highly automated devices. Due to cognitive or physical limitations, some elderly individuals may face challenges in operating complex devices or might be passively subjected to their use without fully understanding their functionality and risks. This underscores the need for user-centered design with intuitive interfaces and multi-level authorization mechanisms, ensuring that users retain control over the device. Additionally, clear user education and support systems should be established to help elderly users and their families better understand and utilize these technologies.

6. Conclusion

The issue of an aging population has become an urgent social issue that the country currently needs to address. Bathing, as an essential part of the daily lives of the elderly, is an inescapable aspect of social elderly care. To enhance the bathing efficiency of the elderly with disabilities and alleviate the pressure on caregiving, bathing aids and robots have emerged as viable solutions. Current research on bathing aids and robots has achieved certain advancements in structural design, motion control, and information perception, demonstrating the significant potential and broad prospects of the market for bathing aids and robots. However, there remains a significant gap between the current state of development and the widespread adoption of existing bathing aids and robots. This gap can be attributed to several factors, including structural complexity, control safety, and the level of integration with information technology, all of which fall short of users' ideal expectations. In future development, it is essential to leverage the advantages of interdisciplinary integration, leading with user needs, and moving towards an integrated and intelligent direction of "materials-structure-control-information integration". This approach aims to achieve diversified, personalized, and modular bathing products, thereby playing a significant role in enhancing the well-being of the elderly in their daily lives.

CRediT authorship contribution statement

Jian Li: Writing – review & editing, Writing – original draft, Supervision, Funding acquisition. **Yadong Mo:** Writing – review & editing, Writing – original draft, Funding acquisition. **Shijie Jiang:** Writing – review & editing, Writing – original draft, Investigation. **Lifang Ma:** Writing – review & editing, Resources. **Ying Zhang:** Writing – review & editing, Supervision, Conceptualization. **Shimin Wei:** Supervision, Resources, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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