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# Brain-Controlled Wheelchair Review: From Wet Electrode to Dry Electrode, From Single Modal to Hybrid Modal, From Synchronous to Asynchronous

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**ABSTRACT** Brain-computer interface (BCI) is a novel human-computer interaction model, which does not depend on the conventional output pathway (peripheral nerve and muscle tissue). In the past three decades, it has attracted the interest of researchers and gradually become a research hotspot. As a typical BCI application, the brain-controlled wheelchair (BCW) could provide a new communicating channel with the external environment for physically disabled people. However, the main challenge of BCW is how to decode multi-degree of freedom control instruction from electroencephalogram (EEG) as soon as possible. The research progress of BCW has been developed rapidly over the past fifteen years. In this review, we investigate the BCW from multiple perspectives, include the type of signal acquisition, the pattern of commands for the control system and the working mechanism of the control system. Furthermore, we summarize the development trend of BCW based on the previous investigation, and it is mainly manifested in three aspects: from a wet electrode to dry electrode, from single-mode to multi-mode, and from synchronous control to asynchronous control. With the continuous development of BCW, we also find new functions have been introduced into BCW to increase its stability and robustness. It is believed that BCW will be able to enter the real-life from the laboratory and will be widely used in rehabilitation medicine in the future.

**INDEX TERMS** Brain-computer interface, brain-controlled wheelchair, electroencephalogram, hybrid brain-computer interface.

## I. INTRODUCTION

In amyotrophic lateral sclerosis (ALS), the degenerated motor neurons contribute to a slow decrease in motor function of muscles [1]. Moreover, people with spinal cord injury (SCI) also have various motor, sensory and sphincter dysfunction [2]. As a result of these diseases, the number of motor neurons in the brain gradually decreases and the information exchange and control between muscles decreases. Thus the brain gradually loses all voluntary actions and control activities. The central nervous system (CNS) has structural and functional plasticity after injury, but this plasticity depends on the functional compensation of the CNS. Functional compensation will not be generated automatically, and it requires specific learning and training [3]. The brain-computer interface (BCI) can replace, repair, enhance, supply

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and improve the normal output of the CNS by detecting the activity of the CNS and converting it into artificial output [4]. And thus, BCIs can realise the direct connection between the brain and the external world as well as helping the recovery of patients' motor and cognitive functions [5].

With the booming of signal processing techniques, the electric wheelchair (EW) control system can be realised by joystick, eye movement or voice [6]–[9]. However, the severity of patients' disease varies from person to person, and these systems are not suitable for users who lack precise control of exercise-related muscle tissues. For some people with a serious physical disability who have lost the living ability, they require full-time assistance in most of their physical movement. The electrical cerebral activity has been already used in several applications that aim to improve the daily life of impaired people with strong motor disabilities. In this paper, we mainly discuss the application of BCI in the field of EW and the development process of BCW. The purpose of this article is to review the origin, development and future of BCW. More specifically, we summarise the development trend of BCW, and it is mainly manifested in three aspects: from a wet electrode to dry electrode, from single-mode to multi-mode, and from synchronous control to asynchronous control. So it can provide technical information for scientific personnel and popular science knowledge for the public. The abbreviations are listed in Table 3 at the end of the text.

Six topics will be covered in this review. First, we will briefly introduce the structure of BCW and list the typical BCW models in the recent fifteen years. Second, we will briefly introduce the research status of the BCW-based EEG signal acquisition system, hoping to have a cheaper EEG acquisition equipment to reduce the cost of BCW. Third, we will explain the BCW controlled by different EEG signals and improve the BCW control mode. Fourth, we will summarise the development trend of BCW from synchronous control to asynchronous control. Five, we will summarise the improvement measures to enrich the functions of BCW. Finally, we will discuss the future of BCW.

## II. THE BRAIN-CONTROLLED WHEELCHAIR MODEL

As a pioneer who helped establish the real BCW model, Tanaka *et al.* first established an EW model controlled by BCI in 2005 [10]. Since then, many scholars have applied BCI technology to EW. We conducted literature searches in major electronic databases, including science Direct, Spinger Link, Google Scholar, and Wed of Science. We set the following search criteria: (1) written in English; (2) published from 2005 to 2019. We set the condition that the only keyword was "brain-controlled wheelchair" as the index. Taking Wed of Science as an example, there has been a significant increase in the number of published articles on BCW over the last 15 years (see Figure 1). The popularity of this topic can be attributed to the broad rehabilitation prospects of BCW for paralysed people locked in wheelchairs. Until now, BCW has made a technological breakthrough in navigating from a simple environment to a complex one. We have listed some typical real BCW models in Figure 2.

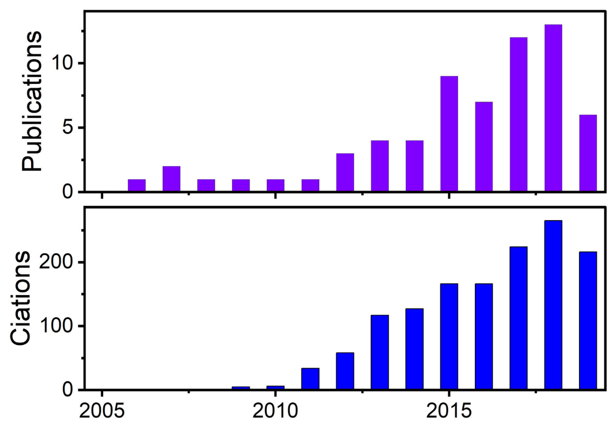


**FIGURE 1.** Publication and citation report of BCW studies for the past fifteen years (2005–2019). Data were obtained in Web of Science using a "brain-controlled wheelchair" as a topic (accessed on 2nd Dec. 2020).

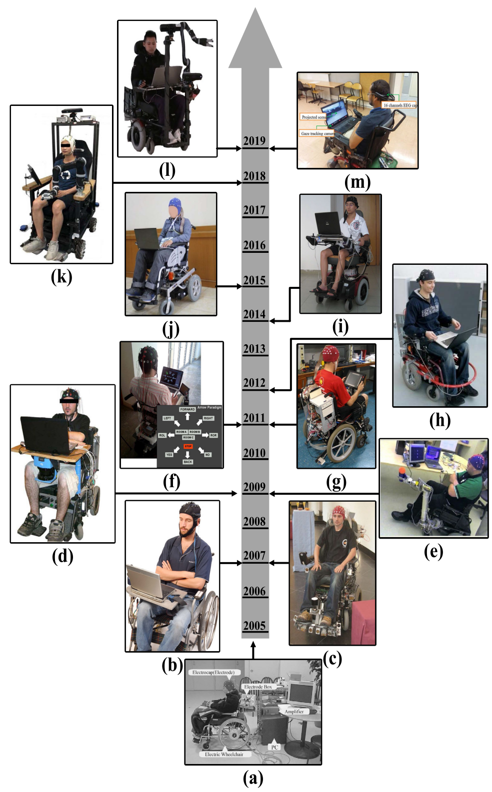


**FIGURE 2.** The typical real BCW models over the last fifteen years: (a) Designed by Tanaka *et al.*, [10]; (b) Designed by Rebsamen *et al.*, [11]; (c) Designed by Vanacker *et al.*, [12], [13]; (d) Designed by Iturrate *et al.*, [14]; (e) Designed by Palankar *et al.*, [15]; (f) Designed by Lopes *et al.*, [16]; (g) Designed by Müller *et al.*, [17]; (h) Designed by Carrino *et al.*, [18]; (i) Designed by Wang *et al.*, [19]; (j) Designed by Turnip *et al.*, [20]; (k) Designed by Bi *et al.*, [21]; (l) Designed by Huang *et al.*, [22]; (m) Designed by Lamti *et al.*, [23].

The real BCW mainly consists of three components: EEG acquisition system, control module, and EW. The EEG acquisition system captures EEG signals from the thinking of the patients' willingness to do, and then transmit the collected

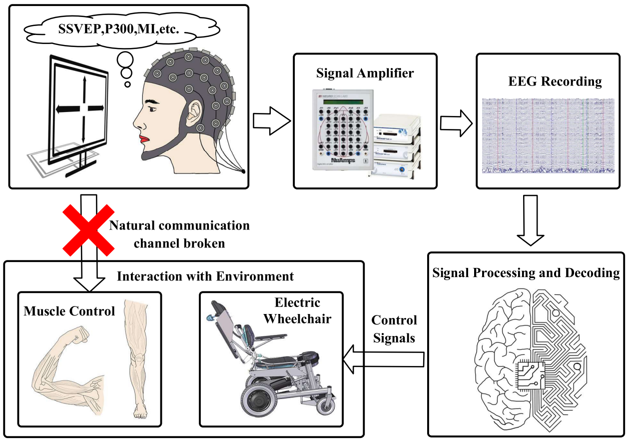


**FIGURE 3.** The control schematic diagram of a brain-controlled wheelchair.

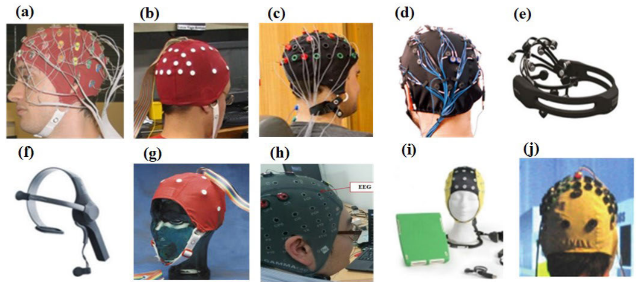

**FIGURE 4.** Example of EEG acquisition system used in BCW applications: (a) Biosemi acquisition system, (b) BrainNet BNT-36, (c) gTec EEG system, (d) Neuroscan, (e) Epoch Emotiv headset, (f) NeuroSky Mindwave Mobile headset 2, (g) BIOPAC$^{TM}$EEG system, (h) gTec EEG system,(i) EEGO$^{TM}$EEG system, and (j) gTec EEG system.

signal to the control module. The control module will extract necessary information which will be used for driving the EW motor. Then, the motor based on the electrical level of the signal performs the predefined operation like rotating or moving the EW in a specific direction [24], [25]. Figure 3 shows a schematic description of a BCWs system, adapted from He et *al.* [26].

## III. FROM WET ELECTRODE TO DRY ELECTRODE

Recording brain activity is the first step in BCW. Although invasive neural signals have a high spatial resolution, there are high safety risks, such as the immune response and callus after surgery. In contrast, non-invasive neural signals are safer than the former because they provide an interface without surgery [27]. The most common physiological signal used in BCW is EEG, primarily because it has excellent time resolution, non-invasiveness, easy to use, portability and relatively low-price [28]. The EEG recording system is composed of an electrode attached cap, signal amplifiers, an analog-to-digital (A/D) converter, and a recording device. The electrodes acquire the signal from the scalp. The amplifiers process the analogue signal to enlarge the amplitude of the EEG signals so that the A/D converter can digitize the signal more accurately. Finally, the recording device, like personal computer, stores and displays the data [29].

The BCW used for rehabilitation training often requires an efficient EEG signal acquisition system to ensure that the collected EEG data is reliable and high-quality. The survey found that the types of EEG caps that have been used in the past 15 years are mainly the following types (see Figure 4). We also summarize those EEG caps that have been widely used BCW in recent years (see Table 1). From Figure 4 and Table 1, we can know that the EEG signal acquisition equipment used in BCW mainly can be classified into two categories: wet and dry. The acquisition methods mainly include wired and wireless. The current mainstream EEG acquisition systems are Biosemi Acquisition System, BrainNet BNT-36, gTec EEG System, Neuroscan, Epoch Emotiv headset, NeuroSky Mindwave Mobile headset 2, and BIOPAC$^{TM}$EEG System. These electrode systems adopt the international 10-20 system to install the electrodes [30]. In addition, the application of wet electrodes in BCW was earlier than dry.

In the first real BCW, Tanaka *et al.* adopt the wet electrode system to acquire and monitor subjects' EEG signals in real-time, giving a reference model to other teams such as Millan *et al.* and Rebsamen *et al.* [10], [31], [32]. Especially, according to the international 10-20 standard, some teams created the simple wet electrodes acquisition source module [33], [34]. A wireless communication headset based on the hydration sensors and Bluetooth technology (Emotiv EPOC headset) was seminally used in BCW [35]. Carrino *et al.* first evaluated this EEG device. It is concluded that the low-cost EEG device can hardly be used for a self-paced BCW system in an error-sensitive context compared [18]. Another commercial EEG device, Neurosky Mindwavd, was also being used to develop BCW [36], which indicated that it is feasible to develop BCW by commercial EEG headsets. We can also see from table 1 that the signal collected by dry electrode systems needs longer duration of the signal for each decoding instruction, and there is no significant difference in sampling rate and decoding instruction number compared with wet electrode system. In general, an efficient BCI system needs a reliable EEG acquisition system and high-quality EEG data [37]. Wet electrodes are usually used for laboratory or medical purposes because it enables researchers to acquire high-quality EEG data. Besides, it can meet the condition that the skin-electrode contact impedance requires less than 50 kΩ in the process of recording clinical EEG signals. Unfortunately, wet EEG signal acquisition equipment has various disadvantages. For example, high prices and time-consuming preparation limit its application in developing BCW [38]. Moreover, wearing this kind of equipment is uncomfortable for some patients, whose electromyogram (EMG) signals may also be represented as an artifact in the EEG signal [39]. Therefore, we should pay attention to eliminating the interaction effect between the EEG signal and the EMG signals during the acquisition of the EEG signal. Occasionally, the electrical

(a) (b) (c)

**FIGURE 5.** Example of dry electrode use in BCW applications: (a) SAHARA. Active dry electrode [37], (b) Cognionics. biological electrical sensors [78], and(c) OpenBCI. Dry EEG Comb Electrodes [79].

equipment around the patient may distort the EEG signals due to power frequency interference.

A typical EEG recording system for BCW should record EEG signals in a noninvasive manner. Moreover, it should be portable, low-cost and affordable to procure [33]. Further, such a system should be convenient to use. Under any circumstances, there should be no compromise with the performance of the EEG recording, even for a longer time duration. According to table 1, more and more researchers preferred to use NeuroSky MindWave headset 2 and Emotiv EPOC headset in BCW in the last few years. These two devices are not only at a lower cost but also are simple in output signal processing. The Emotiv EPOC headset is equipped with 14 EEG channels and 2 Gyroscopic channels [80]. There are several features of NeuroSky MindWave headset 2: raw data and power spectrum (delta, theta, alpha, beta, and gamma) [81]. The Emotiv EPOC headset uses sintered silver chloride electrode systems, which are compatible with conducting gels when using [82]. Nowadays, the dry electrodes were popular because the dry electrodes have the advantage of maintaining structural integrity and electrical properties to prolong duration time [37].

Recently, dry electrode systems, such as g. SAHARA, Cognionics, and OpenBCI have been garnered attention [37], [78], [79] (see Figure 5). There are eight gold-plated pins in g. SAHARA. The main advantage is that there is no limit to mount these electrodes in a conventional EEG cap. Cognionics electric sensor electrodes use a combination of silver and carbon poured on a flexible base, and silver/silver chloride coatings. This design not only makes the equipment flexible and durable but also maintain a high-quality signal. Mahmood *et al.* applied the electrode to BCW and realised the five directions of motion [83]. The extended (5mm) prongs of dry EEG comb electrodes accommodate longer hair while enabling excellent signal quality. The blunt prongs can increase scalp contact, comfort, and wearability [79].

Collectively, the dry electrode system facilitates experiment preparation and avoids electrode paste and the wireless electrode system avoids complicated wiring. This is why Emotiv EPOC headset and NeuroSky Mindwave Mobile headset 2 have become popular in recent years. In [83]–[85], the wheelchair control scheme was based on the EEG interface platform of Emotiv EPOC headset. However, the classification accuracy of this BCI system is low. Ratib *et al.* have developed a low-cost BCW using the NeuroSky MindWave headset 2 and the accuracy rates were over 90% [76]. Permana *et al.* designed a wheelchair control scheme based on the NeuroSky Mindwave Mobile headset 2. From the results, it was difficult to classify more than three classes [77]. This shows that low-cost EEG acquisition equipment is difficult to record higher accurate EEG signals. For BCW, the lack of reliability of the collected EEG signals will cause serious consequences. Unless the signal to noise ratio (SNR) can be improved, the wet-electrode EEG systems commonly used for clinical or research purposes should be selected to record EEG signals. In fact, a growing number of researchers tend to use cheap EEG devices to develop BCW for the development of BCW as low-cost EEG acquisition equipment reduces the research threshold of BCW. However, the quality of the EEG signals collected by these low-cost devices needs to be improved, so it is necessary to design a specific low-cost EEG device for key applications and research.

## IV. FROM SINGLE MODAL TO HYBRID MODAL

### A. SINGLE MODAL BASED BCW

EEG signals can be divided into endogenous signals and exogenous signals. The endogenous signal is evoked by the subject, including slow cortical potential (SCP) and sensorimotor rhythms. Whereas the exogenous signal is evoked by an external stimulus presentation, including event-related potentials (ERP) and visual evoked potentials (VEP) [86]. We find that there is relatively little literature that uses SCP to BCW because the SCP needs a long training period and its low information transmission rate (ITR) [87]. There are three main kinds of EEG signals used in BCW: (1) event-related synchronization and desynchronization (ERD/ERS) of sensorimotor rhythms (SMR) $\mu$ (8-12Hz) and $\beta$ (18-25Hz). The rhythms typically decrease (ERD) during motor imagery (MI) and increase (ERS) during motor relaxation [88], [89]; (2) P300 peak elicited by a visual oddball paradigm [90], [91]; (3) steady-state visual evoked potentials (SSVEP) elicited by a constant flicker at a given frequency [92].

#### 1) MI-BASED BCW

The most widely EEG signal for BCW is sensorimotor rhythm in the real environment. Subjects can freely modulate the SMR during MI [93], [94]. Thus, MI-based BCW could allow subjects' sensorial channels to be dedicated to the maintenance of attention to the environment rather than external visual, tactile, or auditory stimuli. This is an advantage over other BCWs based on the exogenous signal, such as the P300 or SSVEP.

Tanaka *et al.* firstly tried the left and right thoughts to control the direction of the EW, procuring notable success [10]. Lew *et al.* also adopted this mental task to control a simulated wheelchair [95]. Vanacker *et al.* used a mild form of online learning to continuously track the subjects' brain signals. The steering signals were outputted by the classifier, which was composed of a probability distribution of these three possible discrete mental turn commands: forward, left, and right. Due to the limited amount of different mental commands that can be reliably discerned by classifier, a command-to-movement

**TABLE 1.** Summary of EEG cap use in BCW.

| Reference | Year | Cap type | Electrode type | Number of electrodes | Sampling frequency | Output commands | Duration of the signal |
|---|---|---|---|---|---|---|---|
| Tanaka *et al.* [10] | 2005 | g | wet | 13 | 1024Hz | 2; forward in diagonal line left/right | 1s |
| Rebsamen *et al.* [32] | 2006 | d | wet | 15 | none | 4; 4 locations, an "application button" and lock | 100ms |
| Philips *et al.* [13] | 2007 | a | wet | 64 | 512 Hz | 3; forward and turn left/right | none |
| Vanacker *et al.* [12] | 2007 | a | wet | 64 | none | 3; forward and turn left/right | none |
| Rebsamen *et al.* [40] | 2007 | d | wet | 15 | none | 9; 7 locations, an "application button" and lock | none |
| Leeb *et al.* [41] | 2007 | j | wet | 1 | 250 Hz | 4; forward, backward, turn right/left | 1s |
| Galán *et al.* [42] | 2008 | a | wet | 64 | 512 Hz | 3; turn left/ right, and forward | 1s |
| Choi *et al.* [43] | 2008 | c | wet | 5 | 256 Hz | 3; turn left/ right, and forward | 1s |
| Millán *et al.* [31] | 2009 | a | wet | 64 | 512 Hz | 3; forward and turn left/right | 500ms |
| Iturrate *et al.* [14, 44, 45] | 2009 | c | wet | 17 | none | 18; 15 locations, turn left/right and validate selection | 1s |
| Müller *et al.* [46] | 2010 | b | wet | 12 | 600 Hz | 4; forward,turn left/right and stop | 10s |
| Shin *et al.* [47] | 2010 | g | wet | 16 | none | 4; forward, backward and turn left/right | none |
| Müller *et al.*[17] | 2011 | b | wet | 12 | 600 Hz | 4; forward,turn left/right and stop | 10s |
| Lopes *et al.* [16] | 2011 | c | wet | 12 | 256 Hz | 11;forward, right, ror, stop, left, rol, back, 3 locations and basic interaction communication | 175ms |
| Ahmed [35] | 2011 | e | wet | 2 | none | 4; forward, backward and turn left/right | 5s |
| Choi [48] | 2012 | c | wet | 5 | 256 Hz | 3; turn left/right and forward | none |
| Carrino *et al.* [18] | 2012 | e | wet | 10 | 128 Hz | 2; turn left/right | none |
| Jiang *et al.* [36] | 2012 | f | dry | 1 | none | 4; forward, backward and turn left/right | 8s |
| Puanhvuan *et al.* [49] | 2012 | g | wet | 6 | 200 Hz | 13;8 locations, forward, backward, turn left/right, and stop | 2s |
| Leeb *et al.* [50] | 2012 | j | wet | 1 | none | 3, forward, and turn left/right | none |
| Diez *et al.* [51] | 2013 | b | wet | 6 | none | 4; forward, backward and turn left/right | 2s |
| Müller *et al.*[52] | 2013 | b | wet | 12 | 600 Hz | 4; forward, turn left/right and stop | 10s |
| Lopes *et al.*[53] | 2013 | c | wet | 12 | 256 Hz | 7; forward, backward, turn left/right 45º or 90º and stop | 175ms |
| Li *et al.* [54] | 2013 | c | wet | 15 | 256 Hz | 4;turn left/right, speed up and speed down | 2s |
| Kaysa *et al.* [55] | 2013 | e | wet | 4 | 128 Hz | 2; turn left/right | 2s |
| Wei *et al.* [56] | 2013 | e | wet | 10 | none | 4; forward, backward and turn left/right | none |
| Guin *et al.* [57] | 2013 | f | dry | 1 | none | 3; forward and turn left/right | 10s |
| Jayabhavani *et al.* [58] | 2013 | f | dry | 1 | none | 6; forward, backward, turn left/right, start and stop | 10s |
| Carlson *et al.* [59] | 2013 | h | wet | 16 | 512 Hz | 2; turn left/right | 2677ms |
| Kim *et al.* [60] | 2013 | h | wet | 16 | 256 Hz | 5;left, left-diagonal, right, right-diagonal, and forward | none |
| Cao *et al.* [61] | 2014 | c | wet | 15 | 256 Hz | 8; turn left/right, forward, acceleration, deceleration, driving at the uniform velocity,turn on/off | 2s |
| Li *et al.* [62] | 2014 | c | wet | 15 | 256 Hz | 4;turn left/right, speed up and speed down | 2s |
| Bahri *et al.* [63] | 2014 | e | wet | 14 | 128 Hz | 4; forward, backward and turn left/right | none |
| Tello *et al.* [64] | 2015 | b | wet | 12 | 600 Hz | 4; forward, stop and turn left/right | 1s |
| Tello *et al.* [65] | 2015 | b | wet | 14 | 600 Hz | 4; forward, stop and turn left/right | 1s |
| Taher *et al.* [66] | 2015 | e | wet | 14 | none Hz | 5; forward, backward, turn left/right, and stop | none |
| Parmonangan *et al.* [67] | 2015 | e | wet | 14 | none | 4; forward, turn left/right, and stop | none |
| Swee *et al.* [68-70] | 2016 | e | wet | 14 | 128 Hz | 4; forward, backward, and turn left/right | none |
| Sinha *et al.* [71] | 2016 | f | dry | 1 | none | 4; forward, turn left/right, and stop | 5s |
| Puanhvuan *et al.* [72] | 2017 | g | wet | 6 | none | 13;9 target destinations, forward, backward, and turn left/right, | 800ms |
| Dev *et al.* [73] | 2018 | f | dry | 1 | 512 Hz | 4; forward, backward, and turn left/right | none |
| Lahane *et al.* [74] | 2018 | f | dry | 1 | none | 4; forward, stop, and turn left/right | none |
| Zambalde . [33] | 2018 | i | wet | 9 | none | 5; forward, backward, turn left/right, and stop | 3s |
| Cruz *et al.* [75] | 2019 | c | wet | 12 | 256 Hz | 7;forward, back, left90, right90, stop , wc, and exit | none |
| Ratib *et al.* [76] | 2019 | f | dry | 1 | none | 5;forward, backward, turn right/left and stop | none |
| Permana *et al.* [77] | 2019 | f | dry | 1 | none | 5; default/motionless, forward, backward and turn right/left. | 1128ms |

scheme was adopted to ensure that the smooth motion will result from these discrete mental commands [12], [13], [42], [96]. Based on this, Millán *et al.* altered three psychological tasks. Subjects 1 and 2 utilised the three mental commands: the imagination of a left-hand movement, word associations and relaxation. Subject 3 utilised different mental commands: word associations, arithmetic operations, and relaxation. These subjects have achieved a well level of mental control [31]. In [97], each of mental tasks was associated with a steering command, either right or left. An improvement was that if no mental command was delivered, the wheelchair would move forward, thus implicitly executing the third driving command. Carlson *et al.* successfully tested the first patient trial of a MI-based BCW, which represented that the BCW technology can be pushed from the laboratory to the living environment [98], [99]. The control commands of BCW also have been increased. In [100], in addition to the left, right and forward control commands (letter composing, arithmetic and Rubik's cube rolling forward), the additional eyes closed action was used for the on/off command. A more natural and accustomed mapping (left and right MIs to turn left and turn right respectively, feet MI to go forward) was used to control the EW, reducing mental load without remembering the mapping relationship [101]. Extensive investigations have always been done on improving the performance of the wheelchair and ensuring the reliability of the control system. Some investigators mentioned above have modified the psychological tasks, and some of them have increased the classification accuracy of mental tasks by improving the algorithm. Hema *et al.* used only two electrodes to record the EEG changes during different types of MI (left hand, right hand and foot) and tried to classify the MI by using recurrent neural classifiers [102], [103] and Elman neural classifiers [104], [105] as accurate as possible. Velasco-Álvarez *et al.* tested an asynchronous BCI in a virtual environment. Subjects successfully navigated the wheelchair to avoid obstacles by discrete advances and turn with MI commands [106], [107]. The personal digital assistant (PDA) based on MI or electromyography (EMG) provided BCW with a series of humanized functions [108]–[110]. Benevides *et al.* applied PDA to the wheelchair and proposed a reclassification model to stabilize the accuracy of the classifier [111]. In [18], the commercial EEG headset was used to build a MI-based BCW. Carra *et al.* also developed a MI-based BCW with portable and low-cost equipment [112], [113]. The MI-based BCW with a low-cost device has achieved good results in the direction control of the wheelchair with fewer tasks.

Usually, the subjects need multiple psychological tasks to drive the wheelchair to complete a smooth trajectory. Thus, more mental commands were decoded [55], [60], [114]–[121]. In [114], [118], each direction (left, forward, right, backward and stop) of the wheelchair corresponded to a mental task (movement imagery, trivial multiplication, geometrical figure rotation, non-trivial multiplication and relaxation). In the prototype developed by Huang *et al.*, the subjects could rapidly control the wheelchair within a short calibration period, realizing operate the wheelchair to turn left or right, to go straight or stop [117]. Kaysa *et al.* did with raising the right hand and raising the left-hand movement as the input for generating wheelchair movement and used the idle activity as a stopping condition for any wheelchair movement [55]. Yu *et al.* proposed an asynchronous control paradigm based on sequential motor imagery (sMI). Four sMI tasks by sequential imaging left- and right-hand movements in an asynchronous mode were encoded to control six steering functions of a wheelchair, including moving forward, turning left, turning right, accelerating, decelerating and stopping [120].

#### 2) P300-BASED BCW

P300 evoked potentials, mainly located in the central cortical region, are positive peaks in the EEG due to infrequent auditory, visual, or somatosensory stimuli, occurring approximately 300 ms after the event [90], [122]. The lower the probability of relevant events, the more obvious the amplitude of the P300 response [123]. The advantage of BCI-based P300 is that P300 is an internal response, and users can generate P300 without training [124]. Rebsamen *et al.* presented the first working prototype of a BCW based on a slow but safe P300 interface. Specifically, the context-dependent menus of commands simplified the motion control. Through a simple and effective path editor, users can enter the guiding path into the system to help the system adapt to changing environmental conditions. Then, the user's task only included selecting the destination and handling the unexpected situation through a dialogue scheme so that users can control the wheelchair with less attention. According to a predefined path, the wheelchair will move along at last [11, 32, 40, 126]. Although the motion control strategy solved the problem of navigation inside an atypical office or hospital environment without complex sensors or sensor processing, the accuracy of P300 classification was the premise to guarantee the effective implementation of this strategy. Pires *et al.* proposed a full system based on a visual P300 oddball paradigm for wheelchair steering. Temporal features and EEG channels were selected through a Fisher criterion, and the P300 was effectively detected by the common spatial patterns method combined to a Bayesian classifier. Offline classification results have shown the effectiveness of the method [126].

On the BCI2000 software platform, Gentiletti *et al.* replaced the character elements on the classical stimulus matrix of the P300 speller with icons in order to get a graphical user interface (GUI) and then simulated wheelchair in a virtual environment. In their work, two healthy subjects each drove the wheelchair along similar paths and distances [34]. Venkatasubramanian *et al.* developed an interface also based on BCI2000, using P300 signals to control the movement of a wheelchair in a predefined path [127]. Since P300 is an evoked potential, subjects rely on the control system to operate the wheelchair. Scientists often improve the performance of P300-based BCW by navigation strategy. Iturrate *et al.* created a BCW that relied on a P300 neurophysiological protocol and automated navigation. When in operation, the user faced a screen displaying a real-time virtual reconstruction of the scenario and concentrated on the location of the space to reach. The EEG signal processing detected the target location, thereby navigating the subject to the destination while avoiding collisions with obstacles in the environment [14], [44], [45]. Shin *et al.* achieved the wheelchair navigation in four directions (left, right, front and back) with the simple P300-BCI. They used only two electrodes and a reference signal. The experimental results demonstrated the feasibility that simple signal processing interpreted the measured signals to decide a movement direction of the wheelchair [47]. The study laid a foundation for P300-based BCW with asynchronous control mode. He *et al.* proposed a new no-threshold asynchronous brain switch based on P300, which makes decisions according to the results of two classifications rather than a thresholding method to distinguish between the control and idle states. The switch was used for the "start/stop" control of a real wheelchair and it was successfully tested in healthy subjects and patients [128].

### 3) SSVEP-BASED BCW

When the human eye is stimulated by flashing signals with a specific frequency, the brain produces electrical activity at that frequency. EEG changes caused by visual stimulation in a specific frequency range can be adjusted through stimulation [129]. This phenomenon is called SSVEP. SSVEP-BCI is widely used because it does not require long-term training, and it has a high transmission rate and accuracy [130]. Mandel *et al.* believed that the robust classification of SSVEPs in brain activity allowed for the seamless projection of qualitative directional navigation commands onto a frequently updated route graph representation of the environment. They initially realised the combination of SSVEP and autonomous navigation systems [131]. Müller *et al.* believed that each frequency value could be associated with a user command or a users' feeling, so two systems were designed. In the first system, the user can choose a specific place to move. Upon such a choice, the control system onboard the wheelchair generated reference paths with a low risk of collision, connecting the current position to the chosen one. In the second system, the BCI based on the SSVEP can discriminate four classes once per second and it can achieve the control of moving the wheelchair forward, to the left, to the right, or to stop. The stimuli flickering was performed at high-frequency (37, 38, 39 and 40 Hz) and participants expressed neither discomfort nor fatigue due to flickering stimulation [17], [46], [51], [64]. Xu *et al.* further proposed an effective and low delayed asynchronous SSVEPs-based BCI system for practical wheelchair control. The transition state and negative edge detection method reduced effectively potential safety risks and enhanced users' experience by minimizing undesired movements [132]. In [133], the SSVEPs elicited by four different flickering frequencies in a low-frequency region (7 Hz, 9 Hz, 11 Hz and 13 Hz). The wheelchair can move forward, backward, left, right and stop positions, which showed that the SSVEP-based BCI with OAA-SVM classifier and violet color stimuli in the low-frequency region can give a promising way. Turnip *et al.* proposed an extraction method for a BCW by applying a nonlinear adaptive filter on EEG-SSVEP. In addition, the application of an adaptive network fuzzy interference system classifier was proposed. A four-choice signal paradigm with different frequencies (i.e., from 6 to 9 Hz for left, right, bottom, and top, respectively) was used to stimulate the four subjects in the experiment, which showed that the extraction method achieved a very significant statistical improvement in extracting peak amplitude features [20, 135-137]. Lin *et al.* proposed a BCW system based on SSVEP made users be able to drive the wheelchair with forward, stop, and left/right-turn commands according to their intentions. Additionally, a reactive navigation scheme based on an artificial potential field (APF) approach was implemented to improve the security of the proposed system. The scheme was expected to provide a convenient, safe, and comfortable mobile assistance to users who are suffering SCIs [137].

## B. HYBRID MODAL BASED BCW

According to the previous description, we found that more research teams were keen to use MI as the control signal of the BCW relative to P300 and SSVEP, because MI did not need to be induced by external stimulus. The design of the single-mode BCW system has made significant progress in paradigm, brain signal processing algorithm and control system, but there are still shortcomings. For example, BCW based MI needs more practice, which makes the patient fatigue easily, thereby affecting the quality of brain signals. BCW based P300 requires repeated scintillation many times. Repeating scintillation for a long time also affects the brain signal of patients. SSVEP based on BCI control command quantity is influenced by the exciting frequency and other factors. Especially when the number of instructions on the BCI increases, the classification accuracy will decrease. In general, the BCW system also faces some challenges in terms of low ITR, diversified functions/control, human-machine adaptability, robustness, and stability. A potential solution is to use a new type of BCI system, namely the hybrid brain-computer interface (hBCI). Pfurtscheller *et al.* believe that in addition to a simple BCI combination, hBCI types also need to meet the following four criteria [138]: (1) The activity is obtained directly from the brain; (2) At least one of a variety of brain signal collection methods should be used to obtain this activity, which may be in the form of electrical potential, magnetic field or hemodynamic changes; (3) Signals must be processed in real-time/online to establish communication between the brain and the computer to generate control commands; (4) Brain activity results must be provided for communication and feedback control. In recent years, the hBCI standard focused on improving the accuracy of activity detection for healthy subjects and patients and increasing the number of control instructions for better communication and control. We classify the hBCI types into three categories in this paper [62]: (1) hBCI is based on multiple brain patterns; (2) hBCI is based on multiple Biological signals; (3) hBCI is based on multiple sensory stimulations.

### 1) HBCI BASED ON MULTIPLE BRAIN PATTERNS

P300 & MI: Rebsamen *et al.* utilised a P300-based or MI-based brain switch to produce a start/stop command for controlling a wheelchair [125]. Yu *et al.* presented a hBCI, in which the user controlled the wheelchair by alternatively performing an MI task or paying attention to P300 flashing [139]. Long *et al.* designed a paradigm that combined MI with P300. The paradigm allows the user to control the direction (left/right turn) of the simulated or real wheelchair by using left/right-hand imagery. Furthermore, the hybrid manner can be used to control speed. If the user wants to decelerate, the user imagines foot movement while ignoring the flashing buttons on the GUI. If the user wishes to accelerate, then he/she will focus on a specific flashing button [140], [141]. This paradigm addressed the challenge that is difficult for current BCW to provide multiple independent control signals [142].

MI & SSVEP: Bastos *et al.* created a robotic wheelchair commanded by a BCI through SSVEP, MI and word generation. When using SSVEP, a statistical test was used to extract the evoked response and a decision tree was used to discriminate the stimulus frequency. When using MI (left/right hand) and word generation, three mental tasks generated instructions to guide the wheelchair through an indoor environment [143]. Cao *et al.* proposed a hybrid BCI system based on MI & SSVEP, which realised the synchronous control of wheelchair speed and direction as well as an on/off control system for wheelchair control [61].

P300 & SSVEP: In [144], a hybrid asynchronous BCI combining P300 and SSVEP was presented. P300 and SSVEP both can be elicited simultaneously. The control state and target button were determined by both P300 and SSVEP detections and the performance for detecting the control/idle state can be improved by using such a hybrid BCI.

### 2) HBCI BASED ON MULTIPLE BIOLOGICAL SIGNALS

EEG & EMG: Li *et al*. presented a real-time composite brain/muscle interface to control a wheelchair directly by using MI-EEG and EMG signals of gritting the left/right teeth [145]. Jiang *et al.* developed a low-cost prototype that was using MI-EEG and EMG signals. The system can detect and determine the user's intention of at least four directions of motion [84]. Chai *et al.* developed a hBCI home environmental control system for paralytics' active and assisted living by integrating single-channel EMG of occlusal movement and SSVEP. This indicated that combining EEG and EMG can effectively enhance the security and interactivity of the environmental control system [115].

EEG & EOG: Wang *et al.* proposed hybrid EEG-EOG BCI, which combines MI, P300, and eye blinking to implement forward, backward, and stop control of a wheelchair. Users (e.g., those with ALS and locked-in syndrome) can navigate the wheelchair with seven steering behaviors [19]. The paper [146] has developed a novel EOG-based switch, which issues on/off commands depending on whether the user's single blinks are performed in synchrony with the flashes of a switch button. This switch was applied to a BCW which combined a BCI system based on MI + P300 and an autonomous navigation system in [147]. As only one EOG channel was used, the switch was practically feasible in many situations.

### 3) HBCI BASED ON MULTIPLE STIMULATION SENSORY

Another approach to improve the performance of BCIs is to combine different signal modalities or control signals to form a hybrid BCI. To increase the control accuracy of BCI-controlled robotic wheelchair, the new non-traditional control method called "extended BCI" came into being, which involved the operation of multiple control channels in parallel [147].

Multiple modes of operation combined with EEG signals: Bonarini *et al.* developed an autonomous wheelchair that was capable of avoiding obstacles, self-localize and safely explore indoor environments. In the model, the user has the opportunity to choose among several autonomy levels (from simple obstacle avoidance to complete autonomous navigation) and different interfaces: a classical joystick, a touch-screen, an electro biographic interface, and a BCI [148]. The paper [16] presented a new shared-control approach based on P300, which allowed the selection of brain-actuated commands to steer a robotic wheelchair. In such a BCW, at least one specific motor skill, such as the control of arms, legs, head or voice, was required to operate a conventional HMI.

Gestures combined with EEG signals: Real Wheels system incorporated a BCI based on SSVEP along with modifications to existing joystick controllers to operate a controller for wheelchair movement. A series of higher-level navigation commands, called "wheelchair gestures", assist a wheelchair user in accomplishing activities of daily life [149].

Speech recognition combined with EEG signals: Wang *et al.* established a multimodal interface for EW, which had three types of available inputs: speech, keyboard and traditional joystick [150]. On this basis, a BCW controlled by a coordinated mechanism based on a BCI and speech recognition was presented. The coordinated control mechanism had a satisfactory path and time optimality ratios [151]. The speech recognition was a fast and accurate supplement for BCWs. Devi *et al.* added voice recognition sensors to BCW to help the physically challenged people given an effective result with less effort [152].

## V. FROM SYNCHRONOUS TO ASYNCHRONOUS

A BCI system can work synchronously or asynchronously. Up to now, synchronous and asynchronous protocols have been applied to BCW. Typically, the synchronous protocol for BCW was proposed by Rebsamen *et al.* [32], [125]. In general, the P300 [32], [59], [125] and SSVEP [46], [51] was used for selecting the predefined location of the destination. Moreover, an intelligent navigation system was utilised to avoid obstacles by laser sensors and to drive the wheelchair along the specific path [44]. During navigation, the user can only control the wheelchair discretely and cannot modify the specified track arbitrarily. Although the synchronous protocol showed high accuracy and safety [125], the response efficiency of wheelchair control was low, and the selected path was constrained by the operating environment. On the contrary, the asynchronous protocol requires minimum concentration-time and minimum error-detection. The user's intentions are continuously and accurately interpreted into control commands by the BCI, so that the user controls the BCW at their discretion [41], [103], [153]. Rebsamen *et al.* pioneered the asynchronous P300 system user [11]. A representative MI-basedcontrol system was developed by Galán *et al.* [42], [96]. In such a system, the asynchronous protocol was applied to realise the real-time continuous directional control. A self-paced BCW enabled the user to have the option to control the device when required (user has more control) and can avoid obstacles autonomously to provide safer control [166]. Xu *et al.* applied the asynchronous protocol to the SSVEP-based BCW. The Bayesian Classifier and a low-delayed asynchronous detection mechanism were devised and integrated to enable the user to control the wheelchair flexibly [132]. BCWs have been researched by several research groups over the past 15 years, and we summarise in Table 2. Table 2 shows asynchronous BCW has attracted more and more scholars' attention. Asynchronous control protocol means that the user can use low-Level navigation to achieve continuous control of any direction of the wheelchair. In an asynchronous BCW system, brain signals are continuously detected and analyzed by the system. This puts forward higher requirements for EEG signal acquisition, pre-processing algorithm research, software, and hardware processing, etc. At present, the research on asynchronous BCW is still in the laboratory stage, and the methods adopted are mostly based on MI and SSVEP. It is easy to implement the asynchronous BCW based on MI, but there are some disadvantages in MI, such as the small number of categories and training requirements. There are many categories of SSVEP, which do not require training but exogenous stimulation. The asynchronous control of BCW often requires multiple control commands. Researchers are committed to the study of decoding EEG signals and classifying EEG signals with high accuracy. Only by carrying out experiments and analysis, accelerating the speed of signal acquisition and processing, and improving the classification accuracy and the system's usability can asynchronous BCW reach the degree of practicality.

## VI. CHALLENGE AND SOLUTION OF BCW

Although researchers have made great improvements in the control scheme of BCW, the functions of BCW are still lacking, which means that there are still many challenges in achieving the goal of BCW from laboratory to daily life. Over the past 15 years, scientists have been working on solutions to enrich wheelchair functions.

### *A. THE NAVIGATION IN BCW*

The BCI technology can read EEG signals and convert them into real-world motions. However, the collected EEG signals are usually accompanied by noisy signals and hard to analyse. Although some scholars have improved the classification accuracy in algorithms, they still cannot guarantee the user can safely, effectively, and accurately navigate the wheelchair. The P300 BCI-based motion path guidance strategy enabled the wheelchair to safely and effectively navigate in an indoor environment without complex sensors or sensor processing, circumventing the problem caused by the low information rate of the EEG signal [11], [40], [125]. A ''scenario'' stimulation screen optimised the motion guidance strategy [167]. However, in the path guidance strategy, the user's control right will be deprived after selecting the target. The control weight of a user in a shared control system was irrelevant to the user s capability or the driving conditions. Philips *et al.* adopted this method to the BCW, building a semiautonomous system that worked in cooperation with humans. Three levels of assistance (collision avoidance, obstacle avoidance, orientation recovery) were activated only when the user needs them [13]. Vanacker *et al.* improved the shared control system. They used knowledge about the current context to filter out erroneous steering commands and improved the overall driving behavior especially when the subject was not already trained for the task [12]. The shared control system can reduce subjects' cognitive workload [97]. The shared controller coupled the intelligence and desires of the user with the precision of the machine allowed users to dynamically produce intuitive and smooth trajectories, rather than relying on predefined routes. The number of decoded symbols per minute (SPM) in a BCI was still very low, which means that users can only provide a few discrete commands per minute (less than 10 SPM). Thus, the control of the wheelchair should rely on the navigation system. The system received sparse commands from the user and then performed safe and smooth maneuvers according to steering information [59].

The two-layer shared control approach obtain the safe and effective navigation of BCW. The first layer is a virtual-constraint responsible for enabling or disabling the user commands, based on certain context restrictions. The second layer is a user-intent matching responsible for determining the suitable steering command, which was better to fit the user command and taking the user competence on steering the wheelchair into account [16], [53], [158]. In [14], [44], not only the multiple stages of shared control were implemented for a BCW, but also the automatic navigation system was integrated into the BCW to solve the problem of low ITR. Puanhvuan *et al.* proposed a hybrid P300 and eyes-blink with the BCW system which can be operated in both automatic navigation and controlled mode [49]. Rui *et al.* also proposed a BCW system combined with autonomous navigation system [168]. The concept of autonomous navigation gives the user the flexibility to use the BCW in unknown and evolving scenarios. The more difficulties the subjects encounter in driving a wheelchair, the more assistance they should receive. The collaborative control mechanism was put forward to assist users when they need help [169]. The system used some hypothetical methods to predict the drivers' intentions, if necessary, to adjust the control signals to achieve the desired objectives. The human-machine shared control strategy employs both brain-machine control mode and autonomous control mode. In the brain-machine control mode, a novel BCI using SSVEP was utilised two brain signals to produce a polar polynomial trajectory. In the autonomous control mode, the synthesis of angle-based potential field and vision-based simultaneous localization and mapping technique guided the BCW navigating among the obstacles [170].

**TABLE 2.** Summary of relevant research works in the field of BCWs and main characteristics in chronological order. (adapted from Fernández-Rodríguez *et al.* [154]).

| BCW | Year | Signal | Navigation system | Asynch. control | Decoding type | Subjects |
|---|---|---|---|---|---|---|
| [10] | 2005 | MI | Low-level | Yes | Discrete | 6 |
| [11] | 2007 | P300 | High-level | Yes | Discrete | 5 |
| [31] | 2009 | MI | Shared | Yes | Continuous | 3 |
| [14] | 2009 | P300 | Shared | No | Discrete | 5 |
| [132] | 2009 | SSVEP | Shared | Yes | Discrete | 9 |
| [126] | 2010 | hybrid[g] | High-level | Yes | Discrete | 5 |
| [156] | 2010 | P300 | High-level | No | Discrete | 1[a] |
| [47] | 2010 | P300 | Low-level | No | Discrete | 1 |
| [103] | 2011 | MI | Shared | Yes | Mixed[b] | 4 |
| [154] | 2011 | MI | Shared | Yes | Discrete | 2 |
| [118] | 2012 | MI | Low-level | Yes | Discrete | 5[f] |
| [48] | 2012 | hybrid[h] | High-level | Yes | Continuous | 3 |
| [18] | 2012 | MI | Low-level | Yes | Not specified | 1 |
| [157] | 2012 | hybrid[g] | Low-level | Yes | Mixed[b] | 7 |
| [141] | 2012 | hybrid[g] | Low-level | Yes | Continuous | 2 |
| [49] | 2012 | hybrid[h] | The user can choose low or high-level | No | Discrete | 4 |
| [133] | 2012 | SSVEP | Low-level | Yes | Continuous | 2 |
| [114] | 2013 | MI | Low-level | Yes | Discrete | 1 |
| [101] | 2013 | MI | Low-level | Yes | Continuous | 3 |
| [146] | 2013 | hybrid[h] | Low-level | Yes | Continuous | 1 |
| [59] | 2013 | MI | Shared | Yes | Continuous | 4 |
| [53] | 2013 | P300 | Shared | No | Discrete | 11[c] |
| [52] | 2013 | SSVEP | Low-level | asynchronous or synchronous (optional) | Discrete | 1 |
| [145] | 2013 | hybrid[h] | Low-level | Yes | Continuous | 5 |
| [51] | 2013 | SSVEP | Low-level | Yes | Continuous | 13[d] |
| [158] | 2014 | Alpha band | Low-level | Yes | Discrete | 8 |
| [19] | 2014 | hybrid[h] | Low-level | Yes | Continuous | 4 |
| [61] | 2014 | hybrid[g] | Low-level | Yes | Mixed[b] | 3 |
| [62] | 2014 | hybrid[g] | Low-level | Yes | Continuous | 3 |
| [159] | 2014 | SSVEP | Shared | Yes | Continuous | 4 |
| [160] | 2014 | EOG (embedded in EEG) | Low-level | Yes | Continuous | 5 |
| [161] | 2015 | MI | Low-level | Yes | Discrete | 3 |
| [162] | 2014 | SSVEP | High-level | Yes | Discrete | 37 |
| [148]a | 2016 | MI | High-level | Yes | Discrete | 3 |
| [148]b | 2016 | P300 | High-level | Yes | Discrete | 6 |
| [140] | 2017 | hybrid[g] | Low-level | Yes | Continuous | 8 |
| [163] | 2017 | EPR | High-level | Mixed[e] | Discrete | 8 |
| [121] | 2018 | MI | Low-level | Yes | Continuous | 7 |
| [164] | 2018 | MI | Low-level | Yes | Continuou or Switch | 15 |
| [165] | 2019 | hybrid[h] | High-level | Yes | Mixed[f] | 22 |
| [166] | 2019 | hybrid[g] | Low-level | Yes | Continuous | 5 |

[a]Affected by Guillain-Barre Syndrome
[b]discrete turns and continuous advance and recoil
[c]1 participant with cerebral palsy and motor impairment
[d]1 paraplegic participant
[e]An asynchronous mode is used to switch the environmental control system on or off, a synchronous mode is used to improve the accuracy and speed of BCI detection.
[f]Users can continuously steer the wheelchair left/right by imagining left/right-hand movements. Users generate discrete wheelchair commands, such as moving forward and backward and stopping, by implementing eye blinks and eyebrow movements
[g]hybrid Signals based on multiple brain patterns
[h]hybrid Signals based on multiple Biological signals

### B. FUSION OF BRAIN-CONTROLLED WHEELCHAIR AND ROBOTIC ARM

The wheelchair-mounted robotic arm (WMRA) system can reduce the dependence of disabled people using EWs on human aides. As early as 2005, Alqasemi *et al.* developed a 9-DoF WMRA system controlled by a joystick, keyboard, BC12000, and so on to finish the predefine daily task, such as reaching, carrying and placing [171]. The WMRA system met the needs of mobility-impaired people with limitations of upper extremities and exceed the capabilities of BCW [15], [155], [172]. Valbuena *et al.* described a BCI based on SSVEPs used as an input device for the semi-autonomous robot FRIEND IT. The robot is composed of a wheelchair and its mounted 7 DoF manipulator, which can help people to do a series of office, work and spare time [173].

A P300-based interface was used for choosing an action to be performed on the object by the WMRA [174]. Due to some limitations of the single-mode BCW, the hBCI has also been introduced for WMRA control. Achic *et al.* proposed a system consisting of an EW with an embedded robotic arm. It combined a hBCI and shared control system for navigation and manipulation, which can assist users to achieve essential tasks [175]. Chen *et al.* developed a WMRA system using a coordinated control strategy. The strategy was composed of an operating intention expression and identification with EEG, which located objective based on EOG and head gesture and a human-robot interface. In this bionic manipulator system, the system converted the user's control intention into corresponding control instructions. Then, instructions were sent to the actuator of the arm joint motor to realise the motion control of the bionic manipulator [176]–[178]. Huang *et al.* proposed to help the user turns the wheelchair left/right by performing left/right-hand MI, and generates other commands for the wheelchair and the robotic arm by performing eye blinks and eyebrow-raising movements [164]. Tang *et al.* have proposed an improved mobile platform structure equipped with an omnidirectional wheelchair, a lightweight robotic arm, a target recognition module, and an auto-control module. Based on the you only look once (YOLO) algorithm, this system can, in real-time, recognised and located the targets in the environment when the users confirmed one target through a P300-based BCI. An expert system planed a proper solution for a specific target. For example, the planned solution for a door is opening the door and then passing through it. The auto-control system then jointly controlled the wheelchair and robotic arm to complete the operation [179].

### C. BRAIN-CONTROLLED WHEELCHAIRS COMBINED SMART HOME SYSTEM

The lives of most disabled locked in wheelchairs are often boring. The combination of BCW and the smart home system brought fun to disabled people. Qidwai *et al.* modified the BCW. The wheelchair used voice, EEG port, joystick controller as input customised depending on the nature of the disability of the user. It can be used for mobility as well as for controlling the air conditioners (AC) and television (TV) systems [180]. A hBCI home environmental control system for paralytics' active and assisted living came out. The system was designed as a three-level interface. Besides the idle state interface, there are one main interface and five sub-interfaces for the work state. The main interface included five visual stimuli corresponding to different devices such as nursing bed, wheelchair, telephone, television, and lamps. The sub-interfaces presented the control function of those devices. Gazing at stimuli at different frequencies corresponding to a certain function can select a device or device action. Several particular occlusal patterns respectively were used to confirm the selected function, return from sub-interface to the main interface and switch on/off the system [115], [181]. The design concept of the BCW control system indicates that the development trend of the BCW will be combined with the Internet of Things and closer to the lives of patients.

**TABLE 3. Abbreviations.**

| The original words | Abbreviations |
|---|---|
| brain-computer interface | BCI |
| brain-controlled wheelchair | BCW |
| amyotrophic lateral sclerosis | ALS |
| spinal cord injury | SCI |
| central nervous system | CNS |
| electric wheelchair | EW |
| analog-to-digital | A/D |
| slow cortical potential | SCP |
| event-related potentials | ERP |
| visual evoked potentials | VEP |
| information transmission rate | ITR |
| event-related synchronization | ERD |
| event-related desynchronization | ERS |
| sensorimotor rhythms | SMR |
| motor imagery | MI |
| signal to noise ratio | SNR |
| steady-state visual evoked potentials | SSVEP |
| personal digital assistant | PDA |
| electromyography | EMG |
| sequential motor imagery | sMI |
| graphical user interface | GUI |
| artificial potential field | APF |
| hybrid brain-computer interface | hBCI |
| wheelchair-mounted robotic arm | WMRA |
| you only look once | YOLO |
| air conditioners | AC |
| television | TV |
| galvanic skin response | GSR |
| feature-based peak detection | FBPD |
| emotion fractal analysis method | EFAM |
| steady-state somatosensory evoked potential | SSSEP |
| skin conductance response | SCR |
| error correlation potential | ErrP |

### D. REAL-TIME PSYCHOLOGICAL MONITORING

When assistive robots operate in complex environments and the presence of human beings, it will be influenced by several factors that may lead to undesired outcomes: wrong sensor readings, unexpected environmental conditions or algorithmic errors represent, etc.

To guarantee the safety of the user, a possible solution is to rely on a human-supervised approach, another approach is to make wheelchairs semi-autonomous. Diez *et al.* proposed three methods to detect the attention-level of the user based on the alpha rhythm and theta/beta rate. Then use the transitory response of the EEG signal to develop the attention-SSVEP hBCI. This method can determine whether the user is focusing on the stimulus being detected, thereby reducing the risk of wheelchair collision [182]. Cruz *et al.* first analyzed the galvanic skin response (GSR) recorded from healthy and motor disabled people while steering a robotic wheelchair. Then, a method called feature-based peak detection (FBPD) for automatic detection of skin conductance response (SCR) was proposed to infer whether GSR can help in the recognition of stressful situations [75]. Ciabattoni *et al.* proposed the error correlation potential (ErrP) signal detection method for the safe navigation of a smart wheelchair. During wheelchair navigation, possible problems (e.g., obstacles) along the trajectory cause the generation of error-related potentials signals when noticed by the user. These signals are captured by the interface and are used to provide feedback to the navigation task to preserve safety and to avoid possible navigation issues [183]. Lamti *et al.* present a new hybrid system based on the fusion of gaze data and SSVEP. The system not only commanded a powered wheelchair but also accounted for users' distraction levels (concentrated or distracted), which can assess the mental state and mental workload impact on EEG signals to ensure the safety of users [23].

### E. THE NOVEL BCI PARADIGM FOR BRAIN-CONTROLLED WHEELCHAIRS

BCI systems have shown to have a huge impact on the life quality of the disable [4]. According to the foregoing, based on different types of EEG signals (e.g., ERP, SSVEP, MI), different BCWs have been developed. Although those BCWs do not require direct muscle control, they depend to some extent on normal brain function. Damage to the cortex (e.g., ALS or stroke), basal ganglia or other subcortical areas that interact with the cortex (e.g., cerebral palsy), or loss of sensory input (e.g., stroke or SCI) may affect the user's ability to control the cortical potential, or rhythm, or cortical neurons. Therefore, the ability to use a BCW and the best choice between different BCI may vary from user to user. It is need to evaluate specific BCI for specific user for a long-term. BCW should be customized according to the user's situation. Innovation has been achieved in the experimental paradigm of control signals in recent years. For the blind, the vision-based MI BCI paradigm is not applicable. A virtual environment-based training system was devised for a blind wheelchair user using three-dimensional audio supported by electroence-phalography [184]. In the paradigm of visually evoked MI, the graphic interface could distract the subject's attention. The Audio-cued MI-based BCI, as an unconventional paradigm, reduced the probability of misclassification [160], [185]–[190]. A c-VEP paradigm was applied to control the steering of a BCW [191]. Kobayashi *et al.* developed a novel BCI circuit that manipulates an electric wheelchair based on emotion data obtained in real-time by the emotion fractal analysis method (EFAM). Using this BCI circuit allows user to adjust the speed of EW in proportion to the intensity of the emotion [192].

The MI-based system has BCI illiteracy problem and vision-based system (P300 and SSVEP) means that the user needs voluntary gaze control. By the way, ALS patients lose their volitional eye control in the late stages [193]. Kim *et al.* devised a steady-state somatosensory evoked potential (SSSEP) paradigm, which elicited brain responses to tactile stimulation of specific frequencies for the user's intention to control a wheelchair. In the system, a user had three possible commands by concentrating on one of three vibration stimuli that were attached to the left/right-hand and foot, to selectively control the wheelchair (turn- left/right and forward) [194]–[197]. Tøttrup *et al.* investigated the feasibility of decoding covert speech from single-trial EEG and combined it with MI in their study. The experimental results provided new ideas for controlling wheelchairs with the covert speech experimental paradigm [198]. The discoveries of a novel BCI paradigm expand the user group of BCW.

## VII. DISCUSSION

Independent mobility is what researchers are devoted to studying. BCW provides a promising solution for those people with physical challenges has restricted mobility. The most significant advantage of BCW is that the paralysed patient can control the wheelchair directly from the brain signals without the need for speech or physical movement. In early BCW systems, the approach was to use the BCI to select high-level commands (for example, go to the kitchen, bedroom, etc.) and to give the BCW sufficient knowledge and autonomy to execute these commands autonomously. This advanced command can be selected by synchronous BCI [32], [46], [51], [59], [125]. This approach is flexible and adaptive to meet the needs of individual users, which also can be achieved through layered BCI [16], [53], [158]. An alternative approach proposed by Millan *et al.* relied on the concept of shared control. In this method, the user constantly sends commands to the BCW, which perform preset behaviors on a probabilistic basis. This asynchronous control approach gives users autonomy. With the development of computer and sensor technology, hBCIs enriche the control strategy of BCWs and dry electrode technology is also applied to the development of BCWs technology. Using dry electrode system as EEG signal acquisition equipment reduces the cost of BCWs [76].

The structure and function of BCWs have been improved continuously over the past 15 years. Although these results seem promising, the lack of reliable, easy-to-use and portable acquisition systems, as well as semi-autonomous robotic wheelchairs that are robust and safe to operate in living environment, makes it difficult to achieve a BCW for everyday use. Great strides have been made in the field of BCW, but obstacles remain. EEG-based BCW still have the following problems: (1) The placement of traditional wet electrode is cumbersome and the setup time is usually long (up to half an hour, depending on the number of electrodes);

(2) The results of training and learning may not be sustained due to the offset of the electrode position, contact noise with the scalp and other factors; (3) In order to solve the problem of low SNR and online adaptation of subjects, it needs to use powerful amplifiers, efficient machine learning and signal processing algorithms; (4) The attenuation and superposition of brain signals as they travel to the scalp, as well as sparse sampling of brain activity, limit the range of useful control signals that can be extracted.

We think the future of BCW will focus on solving the following problems: (1) To reduce paralysed user effort in controlling the wheelchair; (2) To ensure the safety during movement; (3) BCWs using inexpensive hardware and open-source software; (4) To monitor the activity of the person in real time; (5) The designed system should be portable for the user; (6) The wheelchair has the ability to charge the battery independently.

## VIII. CONCLUSION

This review have introduced an emerging technology of BCW and shown its great prospect in the field of rehabilitation medicine. The emergence of BCW provides a new and feasible human-computer interface for those who suffer from severe dyskinesia, such as ALS and SCI. It can help these patients to interact with the outside world and improve their quality of life. We briefly introduce the BCW related model, structure, and principles of implementation. From the perspective of biomedical engineering research, we investigated many works of literature on BCW, we tried our best to cover those most representative BCW studies, we provided insights into the fundamental basis of BCW technology. We summarize the development trend of BCW based on the previous investigation and it is mainly manifested in three aspects: from a wet electrode to dry electrode, from single-mode to multi-mode, and from synchronous control to asynchronous control. We also summarize the solutions proposed by scholars in the process of improving the function of BCWs. These are the points that other reviews of BCWs have not covered. We hope this paper will help those interested in using or developing BCW technology. Although there are still obstacles in the development of BCW devices to help patients locked in wheelchairs gaining the ability to live autonomously, the desire for personal rehabilitation is strong. With the development of signal acquisition, pattern recognition, artificial intelligence, sensors, and other technologies. We believe that, not long after, it is feasible to design a practical and customized BCW to help patients with severe paralysis for communicating and operating. This technological breakthrough will benefit to more and more paralysed people and greatly help the patients re-obtain the hope of life in the future.

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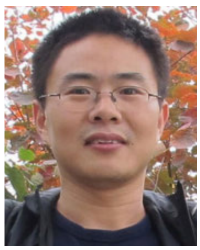

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