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RESEARCH ARTICLE

FBG-based smart bed system for healthcare applications

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Abstract This paper presents a smart fiber Bragg grating (FBG) sensor system with an unobtrusive and easy-to-use FBG sensor bed, which automatically monitors the behavior of bedridden patients and their vital signs based on indicative spatio-temporal signature for adaptive intervention triggering and activity planning. We present the subtle design, fabrication, calibration, implementation and deployment issues of the FBG pressure sensors to be used in hospitals or nursing homes to prevent bedsore generation, patient falling out of the bed, and life-threatening situations such as patient's heart rate weakening, breathing pattern change, etc. Through trials conducted in the laboratory for respiratory rate monitoring with a sample group of 10 subjects, the system showed maximum error of ± 1 breaths per minute as compared to manual counting.

Keywords fiber Bragg grating (FBG), unobtrusive, vital signs, spatio-temporal, pressure sensor

1 Introduction

Non-intrusive, continuous monitoring of the health status and well being of patients on the bed is one of the most challenging and difficult but important problems in hospitals and nursing homes. Ill and frail individuals residing within healthcare facilities such as acute care hospitals, community hospitals, nursing homes and chronic sick units routinely require the monitoring of basic physiological parameters that include body temperature, pulse rate, respiration rate and blood pressure. Such surveillance provides a means for healthcare providers to track the state of health of individuals under their care. For example, an abnormal rise in temperature may indicate the presence of sepsis that would require assessment and intervention. Currently, the measurement and monitoring of such physiological parameters are undertaken by nurses or trained healthcare assistants according to a predetermined schedule, e.g., every four hours or every six hours. Such a process is time consuming, especially in settings whereby large numbers of patients need to be monitored, and utilizes significant resources. Besides temperature, other key vital signs measurements such as respiratory and heart rate are used in the detection of life-threatening situations for bedridden or bed-bound patients, such as frail patients or patients after operation, and in the monitoring of sleep disorders in patients or elderly.

Likewise, detecting or mapping out pressure points on the patients' limbs, which predisposes the patient to develop pressure sores, and monitoring occupancy of patients at risk of falling and detecting when they are trying to get out of bed are important for the care of patients even in acute care ward. Falling is a major issue in the hospital. In 2005, there were over 100 falls recorded in Singapore, and some of them had serious repercussions. Other hospitals and nursing homes have similar statistics. As we can imagine, there are high costs — both in terms of patient's well being and in terms of the impact to the hospital (extra days in hospital/doctor and staff time, etc.). Accidental falls within healthcare facilities can result in untoward outcomes both for the recipients of care and the providers of care. For patients, falls may result in serious injuries such as fractures and intra-cranial hemorrhages; while the healthcare institutions within which such falls occur may likely become victims of litigation.

The current practice is very tedious and time consuming as it typically involves the medical professionals and caregivers having to manually conduct periodic checks leading to unnecessary visitations and delayed response. Furthermore, it is infrequent and may miss onset of crisis event. The use of current commercial systems also faces lots of operational drawbacks for continuous monitoring as they usually involve the patients wearing specialized probes that will constraint their movement and introduce some level of discomfort. Hence, only selected patients in

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critical conditions to be monitored will be wearing the probes. The need to wear probes also limits the practical mass deployment and study on potential clinical problems in patients such as sleep apnea.

Currently, there are research prototypes or systems being developed to monitor parameters such as respiratory rate, heart rate and motion. The techniques are mainly based on wireless, electrical, fluid and optical technology.

For techniques using wireless technology, the state-of-the-art is to use ultra-wide band (UWB) for motion and respiratory rate monitoring[1)] [1]. However, the effectiveness and safety aspects of the system for long-term monitoring are not well studied as they are still in prototype stage. For techniques using electrical technology, majority of the systems are based on piezoelectric sensors. Recent works in VTT done in co-operation with the sensor manufacturer Emfit Corp by Kortelainen [2] propose using electric foil for monitoring respiratory and heart rate. A company named Hoana Private Limited also provides a lifebed patient vigilance system that is able to measure heart rate and respiratory rate through clothing using sensor array and pressure switch that are electrical in nature[2)]. There are also patents [3,4] using camera for detecting the breathing rate of bedded person.

For techniques using fluid technology (such as water, air), there are related works [5,6] on respiratory and heart rate monitoring. For techniques using optical technology, there are three possible sensor technologies, namely, intensity-based optical sensor, wavelength-based optical sensor, such as fiber Bragg grating (FBG), and distributed reflectometry optical sensor for vital signs monitoring. To our best knowledge, there are only a few research groups or companies that use optical sensing technology for continuous non-intrusive monitoring related to healthcare. In Virginia Polytechnic Institute and State University, optical sensors [7] based on distributed reflectometry are used to detect heart and respiratory rate. The fiber technology laboratory in I^2R also conducted research with intensity-based optical sensors [8] for respiratory monitoring. For FBG-related healthcare work, the University of Denver [9] proposed the use of FBG sensor for monitoring temperature of patient in a smart bed sheet but not vital signs monitoring.

While the work in the literature can provide one or two features for monitoring, here, we propose a new single device and technique that will enable one to monitor heart rate, respiratory rate, occupancy and pressure points in a robust manner, taking care of small and big user's movement and selecting the best sensor(s) for performing the monitoring non-intrusively. The FBG sensor system has the potential for allowing automated monitoring of body temperature as well. Such a system, when coupled with a platform for wireless transmission of data, will result in significant time and cost savings and will also allow for more efficient deployment of scarce manpower resources.

2 System setup

The smart multi-functional FBG sensor system consists of the bed sensor array, optical interrogator and PC, as shown in Fig. 1. The software modules are all written in java and communicate through sockets in a distributed fashion. A service-oriented architecture approach is adopted for intelligence, alerting and intervention, as future developers can easily build applications on top of these modules. Currently, our intervention service is to automatically notify caregivers during emergency by sending a short message service (SMS) or through nurse call bell system.

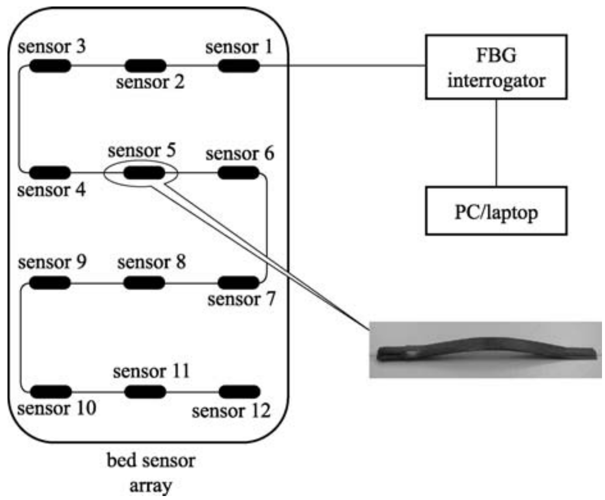

Fig. 1 Single-bed sensor data system deployed in hospital ward

The operation of the monitoring system is kept simple and consists of only three simple steps. Firstly, it uses 12 FBG sensors with different Bragg wavelengths, cascaded along a single fiber. The 12 FBG sensors are mounted on the surface of the bed to form a 3×4 matrix array (as depicted in Fig. 2), and the bed is then covered by the usual mattress. Each FBG sensor is specially packaged into an arc-shaped elastic bending beam using some carbon fiber reinforced plastic (CFRP) material, which ensures excellent sensitivity and good linear translation from a lateral force exerted to the apex of the sensor into axial strain of FBG when a subject is on the bed. Secondly, the optical interrogator is turned on, and the software application is run to acquire all wavelength data of the sensors. Lastly, the body movement and respiration pattern will be captured and displayed once a patient lies on the bed,

1) Pan J L. Medical applications of ultra-wideband (UWB). 2008, http://www.cse.wustl.edu/~jain/cse574-08/ftp/uwb/index.html
2) Lifebed patient vigilance systems. http://www.hoana.com/default.aspx

and intelligent algorithms will show the pressure distribution contour and calculate the respiratory rate. When an abnormal fall in the respiratory rate is detected, an alarm or SMS will be sent to notify the caregiver for immediate attention.

Fig. 2 Sensor array deployment on a bed

3 Sensor design and calibration

3.1 Fabrication of arc-shaped FBG load sensor

A standard telecommunication grade single-mode optical fiber with a 250-μm acrylate coating (ITU-T G.652) is used for FBG fabrication. The fiber is hydrogen-loaded to increase its photosensitivity. Then the acrylate coating of a short section (about 10–20 mm) of the fiber is mechanically stripped off at pre-determined position, and an FBG of about 5 mm long is written into the stripped section using a standard phase mask exposure technique. Blackmann-Harris apodization is applied during grating writing to further improve the Gaussian profile of the reflection spectrum and suppress the formation of side lobes. Immediately after writing the FBG, the fiber containing the FBG is put into an oven for annealing (100°C for 24 h) to stabilize the Bragg wavelength of the FBG.

After annealing, the FBG is packaged into some CFRP material to form an arc-shaped sensor module as shown in Fig. 3(c). The reason for choosing CFRP material for embedding FBG sensor is due to its high strength-to-weight ratio, excellent corrosion resistance and elasticity, low electro-magnetic interference, and ease of molding into complex shapes. The FBG is embedded into 5-ply CFRP laminate with the grating fiber running parallel to the reinforcing fibers of each prepreg, with three plies on top and one ply at the bottom as shown in Fig. 3(a). Since the CFRP prepreg is soft before curing, the arc-shaped metal bridge is used during embedding process and acts as a support to maintain the shape of the arc after curing (Fig. 3(b)). As can be seen from Fig. 3(c), the arc shape of the sensor is maintained after the curing process. The sensor module is 0.625 mm thick, 5 mm wide with the effective length of 40 mm. The height of the arc is 2.2 mm. All the FBGs are calibrated before they are placed on bed for testing.

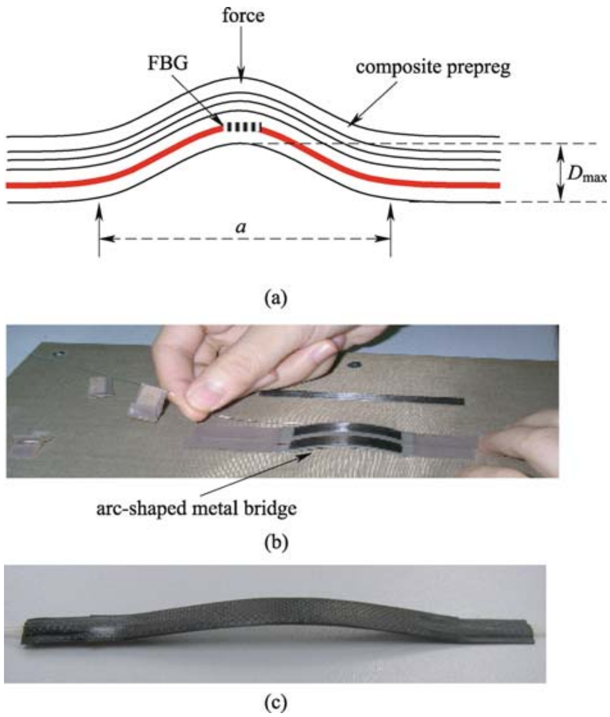

Fig. 3 (a) FBG is embedded into 5-ply composite laminate with grating fiber running parallel to reinforcing fibers of each prepreg; (b) sensors embedded in arc shape (metal bridge acts as a support during embedding and curing process); (c) arc shape of sensor is maintained after curing process

3.2 Calibration of FBG load sensor

In the current setup, all the 12 FBG sensors are placed beneath the mattress. When a person lies on the bed, the apex of each and every FBG sensor may experience different level and frequency of lateral forces as a result of distribution of body weight, respiration and heart-beat-related chest movement. Our main interest is on the vertical force-induced wavelength shift of the arc-shaped sensor module. The peak wavelength/wavelength shift of each FBG is obtained by the FBG interrogator (Micron-Optics Inc. model: Si425-500). The lateral force is applied to the sensor module using Chatillon LF Plus digital force gauge. When the sensor module is under lateral force test (as shown in Fig. 4), a micro-screw meter is used to add force (in the form of vertical displacement) to the sensor, and the arc-shaped sensor module is placed on two metal supports to form a 3-point bending structure. The distance between the two supports is 40 mm (equivalent to the effective length a in Fig. 3(a)). The test is conducted at room temperature. Figures 5 and 6 show the calibration results on one of the sensors. The results show excellent linear

Fig. 4 FBG sensor calibration setup (3-point bending test on arc-shaped FBG sensor using Chatillon LF Plus. FBG interrogator from Micron-Optics Inc. is used to detect peak wavelengths of FBG pair)

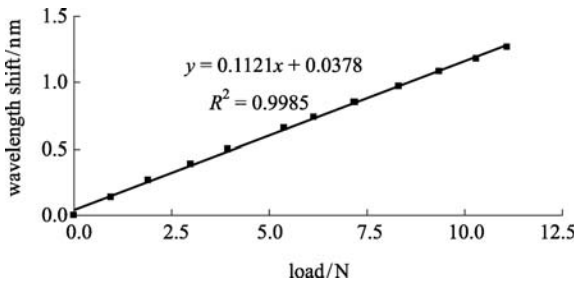

Fig. 5 Wavelength shift versus load/lateral force on arc-shaped sensor module (T = 29°C)

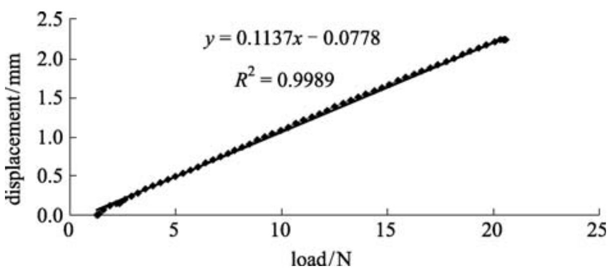

Fig. 6 Displacement versus load/lateral force on arc-shaped sensor module (T = 29°C)

relationship between the wavelength shift/displacement and lateral force. It is also found that the sensitivity can be adjusted by changing the location of the FBG sensor in the CFRP composite or changing the geometry (length, width, and thickness) and the Young's modulus of the sensor module.

3.3 Design and calibration of strain-insensitive FBG temperature sensor

While designing an FBG temperature sensor, the first consideration is how to reduce the strain effect. In this experiment, a 10 mm-long bare FBG is inserted into a 50-mm-long glass tube (with an inner diameter of 3 mm). The bare FBG is pre-curled inside the tube, and both ends of the tube are encapsulated with some potting resin/epoxy (as shown in Fig. 7). The sensor is placed in an oven for calibration; the results show that the Bragg wavelength is increased in a linear manner when the temperature increased from room temperature to around 140°C (as depicted in Fig. 8). It is observed that with every degree Celsius change in temperature, the wavelength will shift 10 pm. The temperature resolution of this sensor is mainly dependent on that of the FBG interrogator. For example, if the resolution of the FBG interrogator is 1 pm (e.g., Micron-Optics SM325 series), with such FBG temperature sensor, we can achieve a temperature resolution of 0.1°C. This should be good enough for body temperature measurement. However, further study on which body part to attach the sensor will need to be carried out, and necessary calibration is required to obtain accurate absolute body temperature readings.

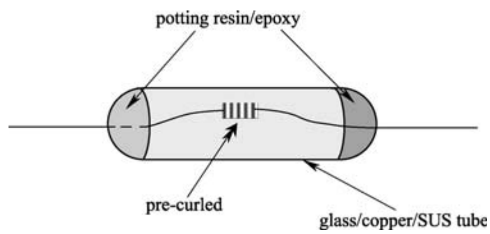

Fig. 7 Structure of strain insensitive FBG temperature sensor

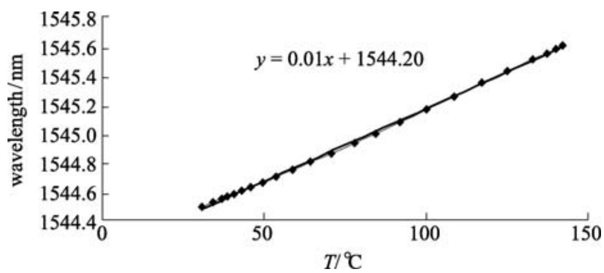

Fig. 8 Calibration results of strain insensitive FBG temperature sensor

4 Data processing

Figure 9 illustrates the break-down of the data processing flow. With normalization, the Bragg wavelengths are removed from the acquired raw wavelengths. In doing so, it returns the relative wavelength differences, instead of the absolute values. In the following, the normalized signal will undergo some filtering. The filtered values will be used to construct the respiratory signal.

Next, wavelet decomposition is used to break down the signal into several levels. The purpose of the decomposition is to remove unwanted frequencies from the signal (arising from other movements in the bed). Subsequently, auto-correlation is applied to observe how the signal changes over time, which amplifies the periodic

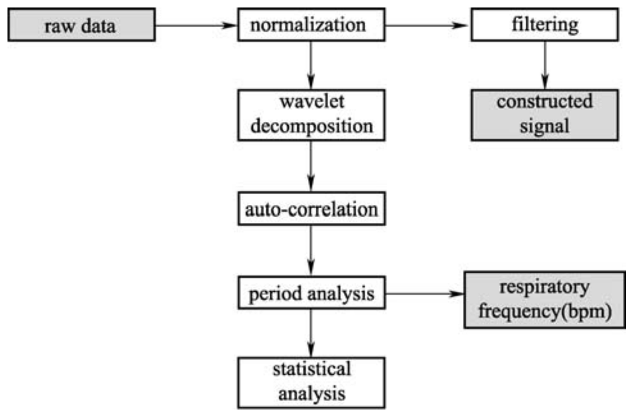

Fig. 9 Data process flow

components, if any. Subsequently, the respiratory frequency will be determined from the pool of periodic components. Lastly, the respiration rate will be tracked so as to observe the change over longer time durations. Some of the screenshots from different stages of data processing flow are depicted in Fig. 10.

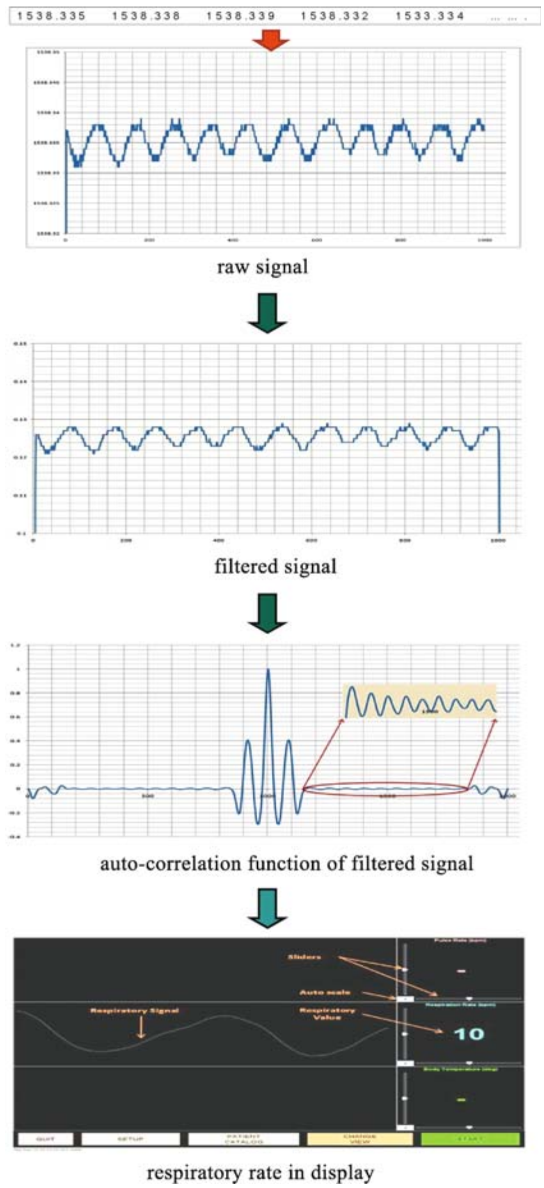

Fig. 10 Data processing flow of respiration monitoring

5 Experimental results and discussion

For monitoring the respiratory rate of the bedridden or bed-bound patients/elderly, we need to consider the different sleeping positions that will affect the sensors. According to a famous study by Professor Chris Idzikowski, director of the Sleep Assessment and Advisory Service in United Kingdom, there are six common sleeping positions as shown in Fig. 11.

We performed many experiments using many different users repetitively on the smart FBG pressure sensor system for monitoring the respiratory rate of a person on the bed according to the six sleeping positions mentioned above. It was found that most of the respiratory rates of patients are around 10 to 25, which is the normal respiratory rate for adults. In order to validate the accuracy of the respiratory rate from our system, we asked the users to mentally count the number of breathing without looking at the system, and almost all values given by users tally with the ones given by the system. We are still in the process of benchmarking it using the gold standards which are the respiratory inductive plethysmogram (RIP) and the airflow measurement methods. Through trials conducted in the laboratory with a sample group of 10 subjects, the system showed maximum error of ± 1 breaths per minute as compared to manual counting.

We also did some preliminary study to measure heart rate relying on simple fast Fourier transform (FFT) techniques to measure the rate after low-pass and band-pass filtering of the signal, but the sensor was placed on top of the mattress in this case. The study showed that the heart rate detected from the FBG sensor is very close to that measured by off-the-shelf pulse oximeter (brand: NONIN; model: AVANT 4000). Further study will be carried out to quantify the accuracy of the heart rate measurement using the FBG sensor.

Figure 12 gives some screen snapshots of respiratory rate and pressure distribution contour when a person is lying on the smart bed.

With this real-time pressure distribution monitoring, when a patient stays unmoved for a long time, it will automatically alert the nurse to help move the patient's body to prevent bedsore generation. In more advanced behavior tracking, the system is able to detect the position of the bedridden patient, whether the patient has fallen off the bed or even to detect the agitation level of a patient.

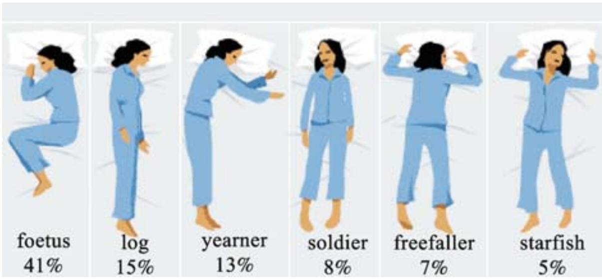

Fig. 11 Six common sleeping positions[1)]

The "through-bed" monitoring approach is possible due to the extremely sensitive nature of FBG, and it allows continuous respiratory monitoring in a non-intrusive manner as the subject only needs to sleep or lie on the bed. In an emergency or abnormal situation, the caregiver can be informed promptly via visual or audio alert systems, or through SMS.

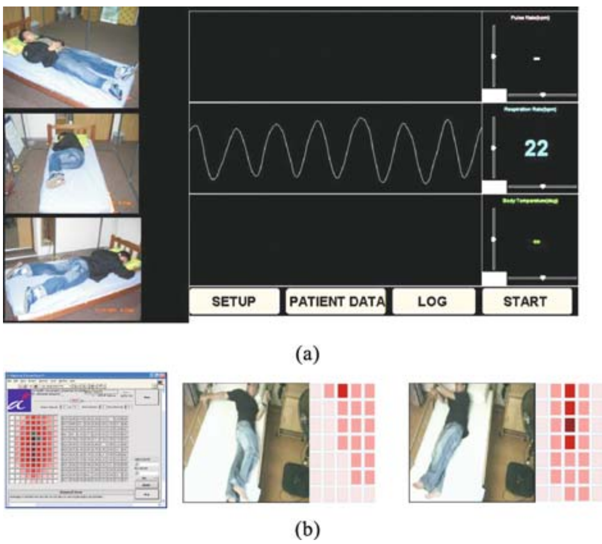

Fig. 12 Screen snapshots when a person is lying on smart bed. (a) Respiratory rate and the waveform; (b) pressure distribution contour when a person is turning left or right

6 Conclusion

We present the subtle design, fabrication, calibration, implementation and deployment issues of the FBG pressure sensors to observe patients in bed and to monitor their vital signs. Laboratory trials were conducted on some of the features to study the effectiveness of such a system. Further study will be carried out to quantify the accuracy of the body temperature and heart rate measurement using the FBG sensor.

The proposed system presents a continuous and non-intrusive approach to monitor respiratory rate, heart rate, pressure points and occupancy of patient on a bed in a robust manner. This method improves the robustness of the system significantly which is very important but not yet well addressed in the literature for non-intrusive monitoring in an unconstrained environment. Such system can be deployed in ward, multiple wards and entire hospital for use with mix of patient types, including mostly bedridden, partially mobile with/without assistance and ambulant, neonates, etc.

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