Autonomous Robots 15, 67–79, 2003

Development of Sensate and Robotic Bed Technologies for Vital Signs Monitoring and Sleep Quality Improvement

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Abstract. More than 50 million people in the U.S. suffer from chronic sleep disorders, including snoring, bruxism, restless legs syndrome, and obstructive sleep apnea. Clinical diagnosis of severe cases often requires expensive, hospital-based polysomnography testing, while less severe cases may benefit from lower-cost in-home sensor systems to collect physiological data over multiple nights. Remedies for sleep disorders, depending on the diagnosis, range from life style modification and medication prescription to throat surgery. There is a need for unobtrusive, in-bed sensing systems as well as robotic devices to alleviate certain sleep disorder symptoms. Two companion devices are presented. The SleepSmart device is a multi-sensor mattress pad controlled by software to detect heart rate, breathing rate, body orientation and index of restlessness. A spectral analysis module is combined with an event detection module to accumulate nightly reports, signal alarms when appropriate and, in future iterations, modify ambient conditions in the bedroom. A companion project has developed Morpheus, a mattress actuation system to encourage a person to roll over in bed to alleviate snoring based on acoustic sensor data analysis. The combination of the two systems is expected to lead to novel, in-home consumer devices to aid persons affected by mild forms of sleep disorders.

Keywords: sleep research, sleep apnea, vital signs monitoring, robot bed

Introduction

More than 50 million people in the U.S. suffer from chronic sleep disorders, including snoring, bruxism, restless legs syndrome, and obstructive sleep apnea (OSA). Clinical diagnosis of severe cases often requires expensive, hospital-based polysomnography testing, characterized by long waiting times due to a lack of availability of instrumented bed suites and a cost of \$1000–\$3000 per night. Less severe cases may benefit from sensor systems that can be used in the home to collect physiological data over multiple nights. A home-use device that has a retail cost of \$2000 can be leased for short-term testing to multiple clients, leading to a cost of diagnosis that may be an order of magnitude less than clinic-based testing. Remedies for sleep disorders, depending on the diagnosis, range from lifestyle modification and medication prescription to throat surgery. This paper presents two companion technologies to help diagnose and alleviate several mild—but prevalent—forms of sleep disorders. SleepSmart$^{\mathrm{TM}}$ is a multi-sensor bed and associated control software to detect body position, surface body temperature, and heart and breathing rates. Morpheus^{TM} is an active bed system that gently encourages a person to roll over to alleviate snoring and OSA. These systems will be combined in a future project to result in a new type of sleep quality improvement system.

Background

Snoring and Sleep Apnea

Snoring is an affliction caused by the relaxing of the muscles located around the upper respiratory tract. As shown in Fig. 1, the collapsed tissues reduce the cross-sectional area available for the air to flow during breathing. The relaxed tissues start to vibrate from the increased airflow speed, producing the low-frequency sound that characterizes snoring. Obstructive Sleep Apnea (OSA) is provoked by the relaxing of the same muscles, but it is a more disruptive and dangerous condition. OSA can cause the interruption of breathing for minutes, significantly reducing the restfulness of sleep since the apnea episodes prevent the sleeper from reaching deep sleep states (stages 3 and 4) for sustained periods of time. In extreme cases, OSA can even cause death.

Both snoring and OSA are typically more intense when the sleeper is in a supine position rather than on the side (lateral position) or prone. In fact, if the supine position is avoided, the relaxed throat muscles are less inclined to move downward and obstruct the airway (Penzel et al., 2001).

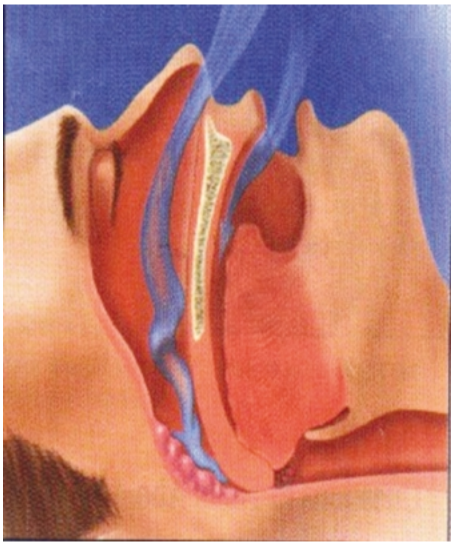


Figure 1. In the supine position, the tissues at the back of the throat compress downward due to gravity, partially closing off the upper respiratory tract.

The prevalence of snoring is as follows: 30% of those over age 30 snore, rising to 40% in middle-age, with a male:female ratio of 2:1. This gender gap closes after menopause, however. Few children (5.6%) are habitual snorers. Four percent of middle-aged men and 2 percent of middle-aged women (18 million Americans) have sleep apnea along with excessive daytime sleepiness. Individuals with untreated OSA are up to 4 times more likely to have a stroke and 3 times more likely to have heart disease. People suffering from OSA are six times more likely to be involved in a car crash (as a result of drowsiness resulting from the reduced restfulness of sleep) than those without sleep disorders (Put an End to Snoring website).

Monitoring Systems

To monitor physiological signals from a sleeping person, clinicians rely largely on wired sensors affixed to the sleeper's body with adhesive tape, straps, elastic bands or clamps. Polysomography systems (Dement et al., 2000) use wired sensors and video monitoring to measure vital signs (breathing and heart rate, blood pressure), chest wall expansion, airway pressure changes and exhaled air CO_2 content, electroencephalogram (EEG) and body orientation. While this provides a rich data set for the diagnosis of severe sleep disorders such as OSA, it is expensive and can only be done in the unfamiliar environment of a clinic over one or two nights. A home version of this system is marketed by SleepSolutions (Palo Alto, CA). The system consists of a data logger with several disposable, wired sensors donned by the person just before going to sleep. The sensors measure heart rate, blood pressure, blood oxygen content and inhale/exhale air velocity at the lips. After two weeks, the logger is returned to the company and the patient's clinician can analyze the data set. A third mechanism to collect sleep data is through surveying patients and their guardians/parents/partners. While the easiest methodologically, this is the least powerful clinically. Actigraphy (Chang et al., 1999; Cole et al., 1992) unobtrusively measures gross body movement with a wrist-watch-type data logger that can be worn nightly for weeks. An increase of restlessness has been shown in some cases to correlate to a decrease in sleep quality. In a similar manner, an experimental ring that performs blood oximetry and measures heart rate optically has been developed to send data to a bedside receiver via telemetry (Yang et al., 1998). Another recently commercialized device is the LifeShirt (Sensatex web site; Gopalsemy et al., 1999), an undergarment with woven-in wires and snaps to connect to sensors, and a wearable computer for telemetry to a base station. The sensors can measure vital signs such as breathing rate and heart rate.

While these sensor systems are person-based, there is another class of bed-based sensors. Many devices have been developed and patented for body position, breathing rate, and heart rate (e.g., Bartels and Harder, 1991) using force sensitive resistors, capacitive sensors, piezo-electric sensors and microphones. However, they can be expensive and may still require wired electrodes for many of the sensing functions (e.g., Crown Therapeutics; Biosaca). Several hospital beds have been developed to provide a constant-temperature, low-pressure environment for persons recovering from pressure sores (e.g., Hill-Rom, Batesville, IN, USA), but no bed-based sensing systems are currently used clinically to diagnose or treat sleep disorders.

Systems to Alleviate Sleep Disorders

Most devices that force the sleeper from a supine to a lateral position are uncomfortable. Their basic goal is to avoid the supine position by a "backpack" that makes it uncomfortable to turn on one's back. A low-cost version of this is a tennis ball sewn into the back of the pajama top. An electrically-actuated, tilting "Pillow for controlling snoring" has been developed in Japan (US patent 4941478, 1990). Several active beds have been designed to encourage a person to change sleeping position. A simple 2-part bed frame (US patent 5042097, 1991) has been invented to encourage someone to turn from a supine to a lateral position: the two halves, hinged longitudinally in the middle of the bed, can be tilted up one at a time. A German patent (PTC/EP85/00714, 1985) shows a bed divided into 3 parts that could be used for the same purpose. The Morpheus 4-segment bed frame described in this paper represents improvements on this prior art due to the increased degree of adjustability in the mechanism, increased safety for the sleeper from falling off the bed during tilting, and increased responsiveness due to the feedback from the sensing of the actual position of the sleeper.

Design of the Proposed Systems

SleepSmart Project

Rationale and Approach. The goal of the SleepSmart$^{\text{TM}}$ Project was to develop a low-cost, multi-sensor, modular, unobtrusive bed sheet that was passive, breathable, impervious to liquids, and washable. The frequency-based software algorithm requirements included heart and breathing rate, body position and motion, and surface temperature (also used as a redundant sensor for body presence). The event-based diagnostic module reduces and stores data to allow 24 hour reporting as well as recognizing and alerting the medical staff in the case of clinically-derived alarm conditions. For home-based sleep quality applications, the SleepSmart concept includes a higher layer of user-interface software to query the individual about daily activities and correlate sleep physiology with daily events that may be mediators of sleep quality.

SleepSmart Design. The approach of the SleepSmart$^{\text{TM}}$ system (U.S. patent 6,468,234; see Figs. 2 and 3) is to use an array of 54 force sensitive resistors (FSRs) and 54 resistive temperature devices (RTDs). RTDs are factory-pre-calibrated. FSRs are calibrated by using known weights and recording the signal output. Since it is not important to perform precise measures of force, but rather detect changes in loading, calibration accuracy is not essential. The FSR amplifiers are set to saturate the 12-bit A/D converters at approximately 200 N. The array is denser (10 cm spacing) under the torso than the legs (20 cm spacing). After the initial amplifier stage, all of the sensors have a 10 Hz cutoff low-pass filter stage. In parallel, twelve of the torso FSRs have a high-gain AC-coupled signal conditioning circuit (with a 0.3 to 20 Hz bandpass filter) to facilitate heart beat detection. All 120 channels are recorded at a 100 Hz sample rate. Digital wavelet transformation software measures average heart and breathing rates at a resolution of 0.5 beats or breaths per minute using "25 second data sets" updated every 5 seconds. Body center of mass is measured using moment calculations of the low-pass-filtered FSR (Force-Sensitive Resistors, model 406, Interlink Corp., Camarillo, CA, USA) and RTD (Resistive Temperature Device 6-S247PF12, Minco Corp., Minneapolis, MN, USA) signals. A restlessness index is calculated by integrating the absolute change in body center of mass over the duration of sleep at "25 second intervals".

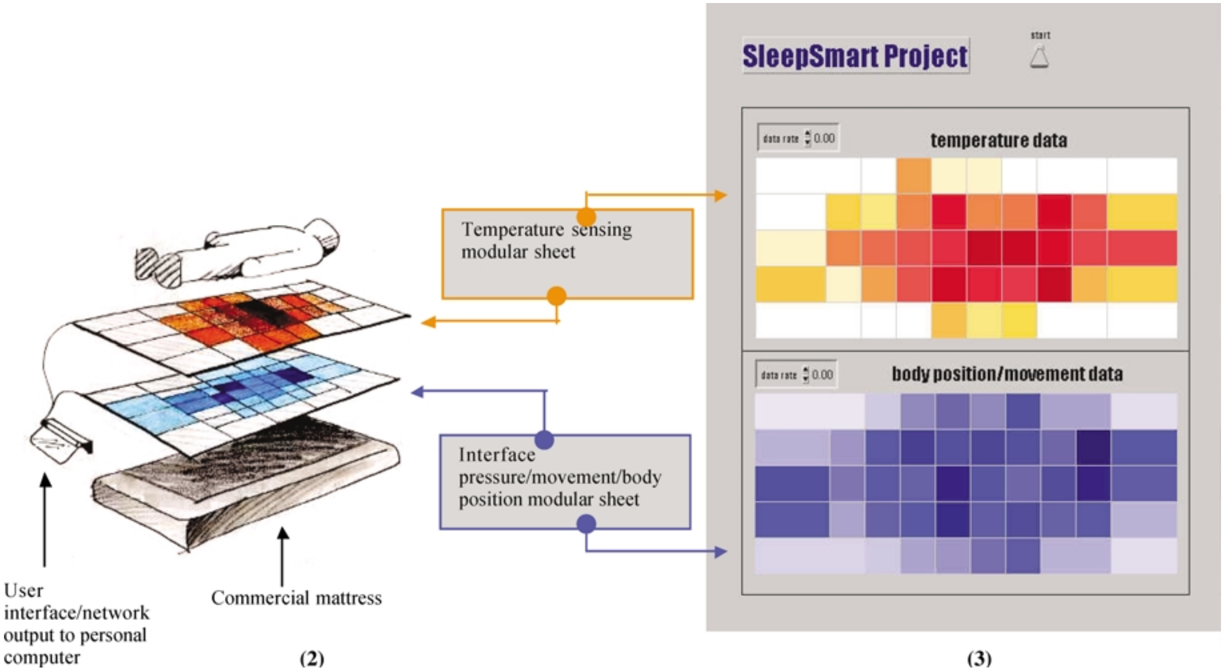


Figure 2 and 3. Prototype concept demonstrating layered sensor approach; each layer can be updated/removed depending upon the users' needs or new technological innovations, and Fig. 3 shows Graphical user interface concept for clinical studies; pressure/temperature information is displayed chromatically and recorded for analysis.

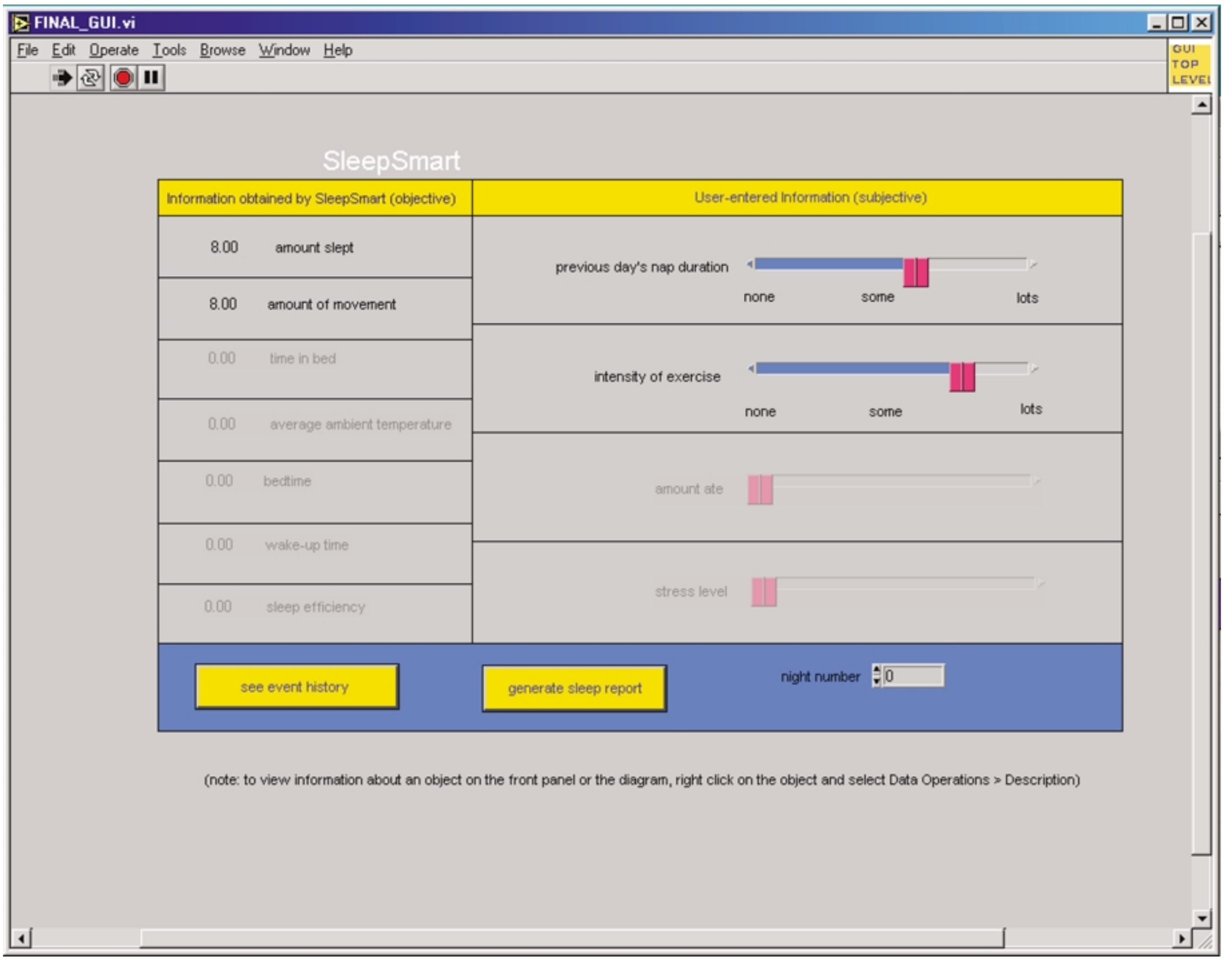
SleepSmart Sleep Quality Software Design. Coupled with this sensing system, a sleep quality improvement software package has been prototyped change to understand the correlations between daily activity stressors and sleep physiology. A daily computer-administered questionnaire is taken before going to bed with a subset of the same questions that a sleep disorder clinician would ask (see Fig. 4), namely questions relating to, for example:

when the last meal was taken,
how recently drinks containing alcohol and caffeine were ingested,
how recently and how strenuous the last exercise was,
how stressful the workday was,
how stressful other interpersonal relationships (e.g., spouse, boss) were,
how long a nap was taken after lunch.

A correlation matrix could then be constructed relating sleeping physiology to waking activity parameters (see Fig. 5). While this design has been developed and implemented, no data sets have been tested.

On a weekly or monthly basis, a person could query the interface software to display graphically the trends and correlations between daily activities and the events extracted from the real-time data. This consumer-level device, still in prototype form, could become a product offering to complement clinical consultation, and may be especially useful in cases of mild forms of sleep disorders not warranting in-depth, expensive clinical case study diagnosis.

SleepSmart Results. Bench testing has shown that heart rate can be measured reliably if an FSR sensor is within 5 cm of the projected location of the heart on the mattress and is not significantly affected by body orientation. The wavelet transformation software analyzes the signal from the 12 torso sensor locations. The output is a set of signals with a significantly better signal-to-noise ratio in the frequency band of interest. A power spectrum analysis is then performed on the 12 outputs, and the one sensor of the 12 that has the highest amplitude in the frequency band of interest is selected. The heart rate is computed as the frequency associated with the highest peak of that one sensor.



SleepSmart

Information obtained by SleepSmart (objective)

8.00 amount slept
8.00 amount of movement
0.00 time in bed
0.00 average ambient temperature
0.00 bedtime
0.00 wake-up time
0.00 sleep efficiency

User-entered Information (subjective)

previous day's nap duration: none some lots
intensity of exercise: none some lots
amount ate
stress level

night number 0

(note: to view information about an object on the front panel or the diagram, right click on the object and select Data Operations > Description)

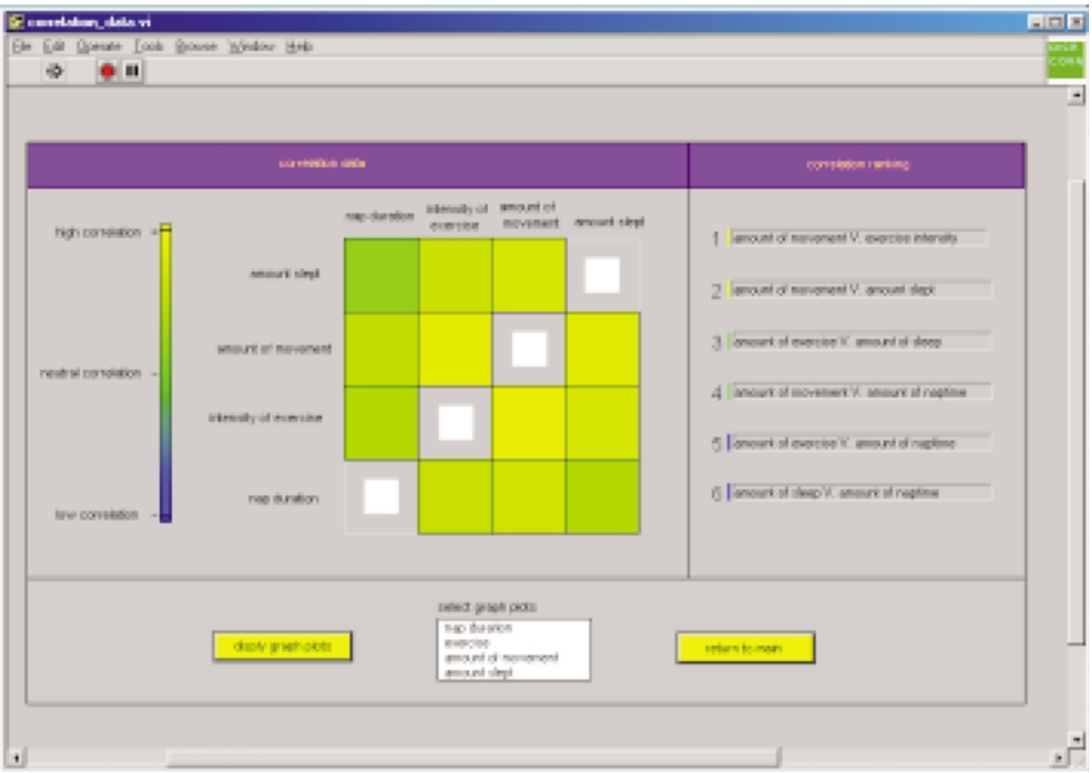
Figure 4. LabVIEW front panel showing a recap of the previous night's parameters (left column) and a questionnaire to be filled out by sleeper (right column) on previous day's activities. If the "generate sleep report" button is pressed, a correlation is performed.

Breathing rate software uses a similar algorithm, but the chest wall movement is readily measured at a number of the sensors due to its gross nature.

Vital Signs Measurement Validity Study. The SleepSmart system was tested in the Sleep Disorder Clinic of the Pulmonary Service of the Palo Alto VA Health Care System with one subject, under the supervision of Dr. Ware Kuschner, MD, and James Canfield, the technologist of the clinic. The subject was asked to sleep for one night on the mattress that was covered with the SleepSmart sheet. He read and signed the Human Consent Form.

The bed mattress was a regular spring and foam clinical mattress, and is considered to be very soft. One regular sheet covered the SleepSmart sheet. The subject slept under one sheet and a blanket, and used a pillow. The ambient temperature in the hospital was approximately 24°C. A separate clinical vital signs monitor recorded heart rate and breathing rate the entire night. The entire night was videotaped. A review of the videotape showed that the subject slept on his back the entire night, making very few leg motions and never turning over to either side. The subject went to bed at 23:10 and woke up at 05:20 the next morning. In addition, he got out of bed from 05:03–05:06.

A gradual increase in maximal recorded temperature starting at 23:10, reaching an asymptote at 37°C in about 1 hour (see Fig. 6). There was never more than ±1°C change the entire night (resolution of the sensors ±0.1°C). At 05:03, the temperature started to reduce, and reached 32°C before the subject returned to bed.



1 amount of movement V. exercise intensity
2 amount of movement V. amount slept
3 amount of exercise V. amount of sleep
4 amount of movement V. amount of naptime
5 amount of exercise V. amount of naptime
6 amount of sleep V. amount of naptime

Figure 5. LabVIEW front panel showing a correlation matrix between daily activity and sleep parameters. Color-coding (from yellow to blue, indicates more or less correlation between categories. The list on the right indicates the top correlations found.

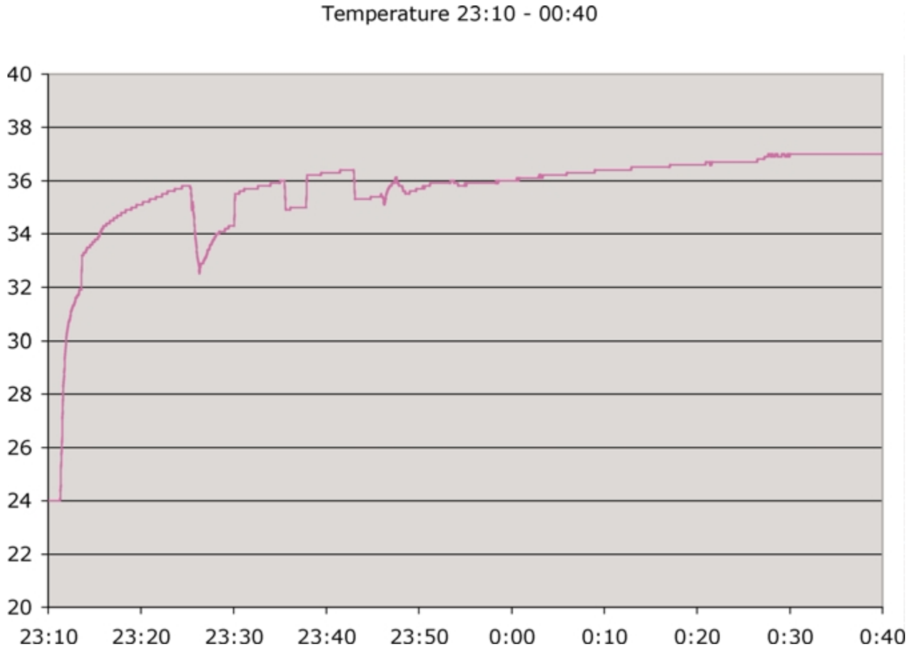


Figure 6. Temperature evolution starting at the time the subject went to bed. A characteristic first-order asymptotic rise from the ambient temperature of 24°C to 37°C.

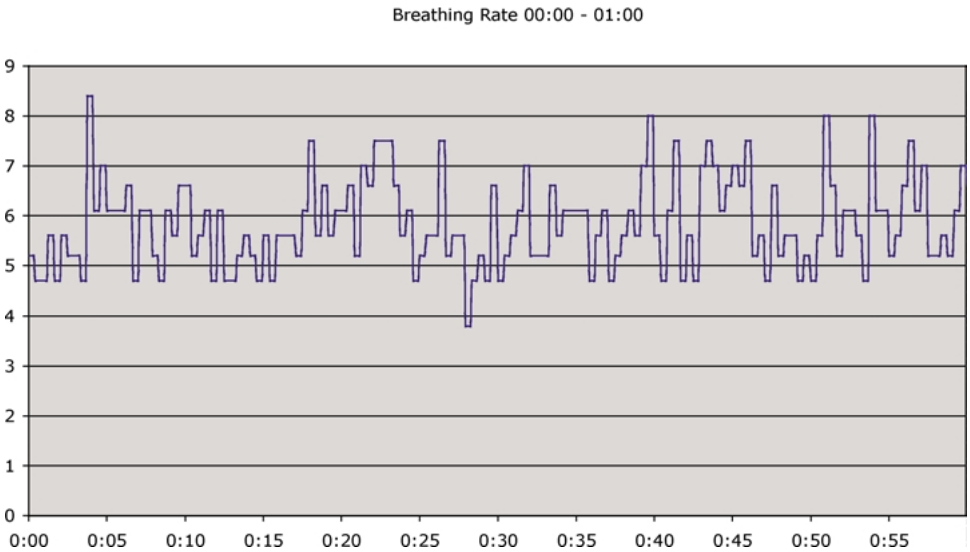


Figure 7. Breathing rate detected between midnight and 01:00.

The temperature increased until he got out of bed at 05:25, and then decreased to ambient. The breathing rate had a mean of 5.83 respirations per minute (sd 1.18) the entire night (see Fig. 7 for a representative hour). Every 5 seconds, posture and temperature maps were recorded, as well as the center of pressure and temperature calculations (see Fig. 8 for a representative image).

To illustrate the potential for the sensing system to be used to detect and warn of emergency conditions, Figs. 9 and 10 show the breathing rate and temperature, respectively, for the period of 05:03–05:06 that the breathing rate decreased to zero, consistent with the subject leaving the bed briefly.

In this preliminary trial, we were able to show that the SleepSmart analysis software can detect breathing rate and temperature changes over an entire night. It detected postural and temperature histories and changes over that span of time. For this test, we were not able to reliably measure heart rate. This is likely due in part to the choice of mattress and partly to the breathing masking the pressure changes associated with the beating of the heart. Future plans include modification of the wavelet transformation software to extract the heart-rate information reliably.

The Morpheus Project

Rationale and Approach. The goal of the Morpheus^{TM} project was to design and implement an adjustable bed frame that, in case the supine sleeper is sensed to be snoring or having an apnea event, should gently encourage the person to turn 90° to one or the other lateral positions, thereby reducing

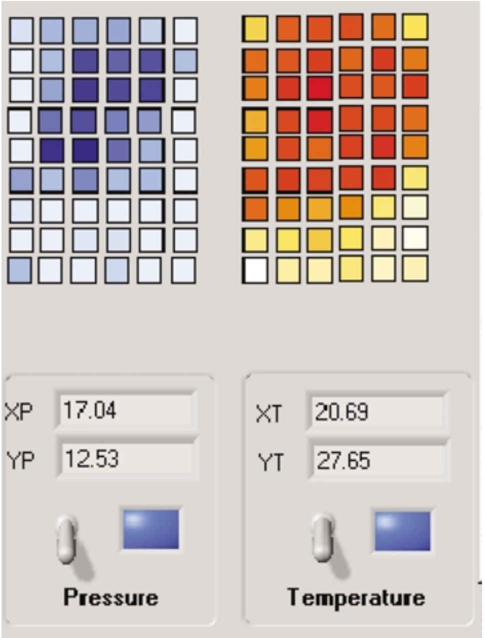

XP 17.04
YP 12.53
XT 20.69
YT 27.65

Figure 8. At time 01:59, these plots represents the pressure (left) and temperature (right) distributions recorded from the sensors. The center of pressure (XP, YP) and center of temperature (XT, YT) show that the sleeper is close to the bed's midline ($X_m = 18$") and closer to the head than the foot of the bed.

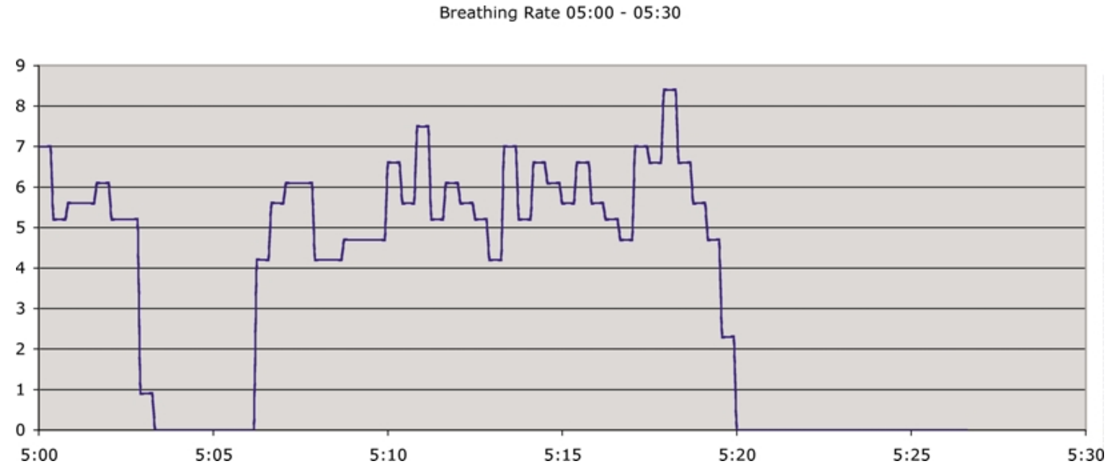


Figure 9. At time 05:03, the breathing rate abruptly changed from approximately 6 breaths per minute to zero, returning to normal several minutes later, indicating that the subject left the bed and came back. At time 05:20, breathing rate again dropped to zero, but then remained constant, indicating that the subject got up to start his day.

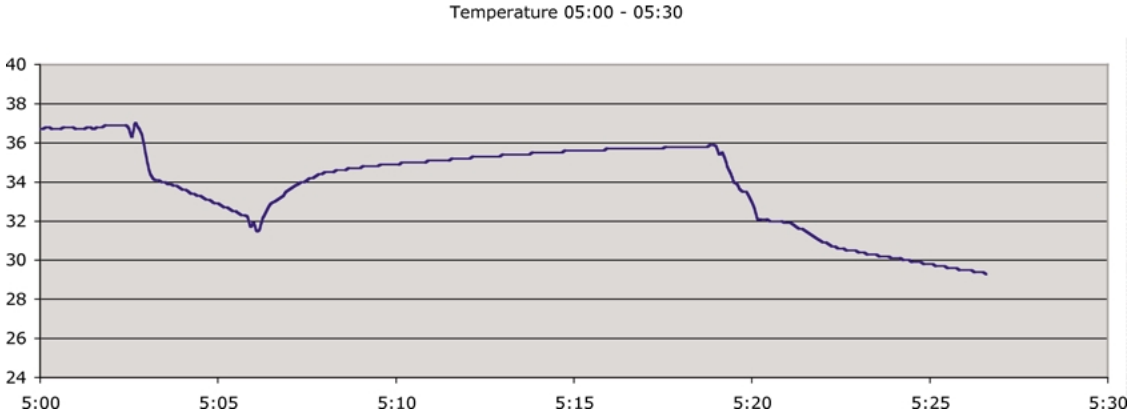


Figure 10. At time 05:03, the temperature began to drop from 37°C, and started rising again coincident with the return of normal breathing (see previous figure). At time 05:20, another temperature drop was noted, with the now-empty bed returning to ambient conditions.

the throat tissue tendency to obstruct the airway. This physical encouragement should be gentle and discreet so as not to wake the sleeper, or at least make it easy to fall asleep afterwards (see Fig. 11).

In order to do so, the Morpheus-Bed is able to perform the following tasks:

- acquire information about the sleeping position of the person on the mattress;
- acquire information about the sleeping posture of the sleeper;
- acquire the sound produced during sleep;
- detect if the patient is snoring or is affected by sleep apnea;
- stimulate physically but gently to encourage the sleeper to turn on one side.

Design of the Morpheus Bed Frame. The Morpheus-Bed is similar in construction and materials to beds for the hospital and the home that have articulated segments; however, instead of lateral hinges to individually lower the head and foot of the bed, the hinges are longitudinal. The Morpheus bed is composed of the following subsystems:

- a bed frame divided longitudinally into 4 tilting segments, actuated with 3 electric motors (one for the two medial segments together, and one each for the

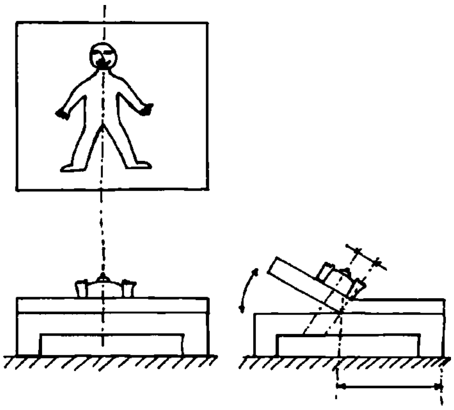


Figure 11. Depiction of first-generation prototype used to test tilting preferences.

two lateral segments), to adjust the sleeper's position (see Fig. 12);

- a data acquisition system to acquire sound and posture/position data and transmit them to the computer;
- a data processing and motion control computer with input/output hardware and control software to evaluate the data provided by the sensors, analyze the sound in order to detect snoring, and output commands to drive the bed motors.

Morpheus User Preference Testing. In order to acquire preliminary user preference data, a first-generation "full" size (width ~160 cm) prototype bed frame was constructed of wood. This frame had only two segments and was adjustable on only

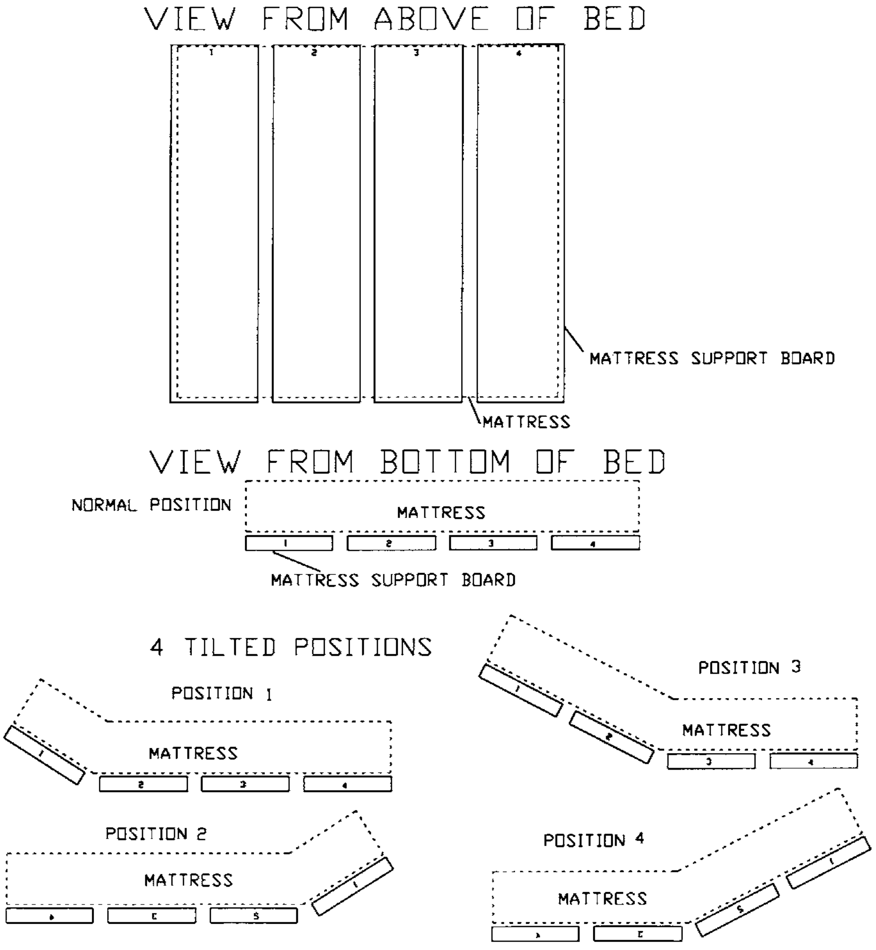


Figure 12. Design of the Morpheus bed, showing the 4 segments and the various combinations of tilts made possible by the hinges of the frames.

one side, one fixed horizontally and the other lifted with the help of an electric winch (see position 3 in Fig. 12). A total of nine test-subjects were asked to lie on the bed and to assume a pre-sleeping position. The section was then lifted to different tilting angles, and the persons were asked about their opinion on (a) a comfortable segment width, and (b) a bed angle they would consider sufficient to encourage rolling over, but still safe. Most subjects liked the basic idea of a tilting roll inducer. A consensus emerged that the portion of the bed that remained horizontal should be at least half the 160 cm bed-width to have an adequate safety margin against rolling completely off the bed, and most subjects suggested a tilting angle of approximately 20°.

Morpheus Pre-Production Prototype Design. A second-generation, metal bed-frame was constructed, as seen in Figs. 13 and 14. The supporting structure is made of steel (see Fig. 13, the dark parts), while the movable parts are mainly made of aluminum alloy (see Fig. 13, the light parts). As seen in Fig. 4, the outer main frame can tilt about a longitudinal axis positioned in the center of the chassis. The two lateral mobile subframes are attached to the main tilting frame by longitudinal hinges. The frames are actuated by 3 electric linear motors removed from a commercial hospital-bed (and therefore noiseless in operation), so that each section can be tilted up to ±25°, with 3 goniometric sensors (potentiometers) acquiring the tilting angles. The four wooden planks that support the mattress are held onto the articulating frame segments with locating pins.

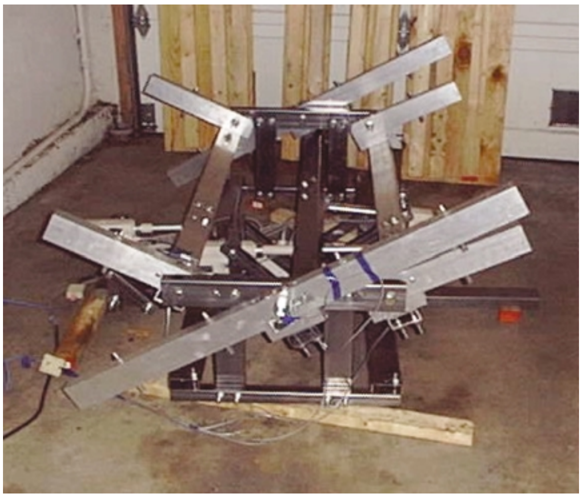


Figure 13. Bed frame with wooden segments removed to show subframe assemblies.

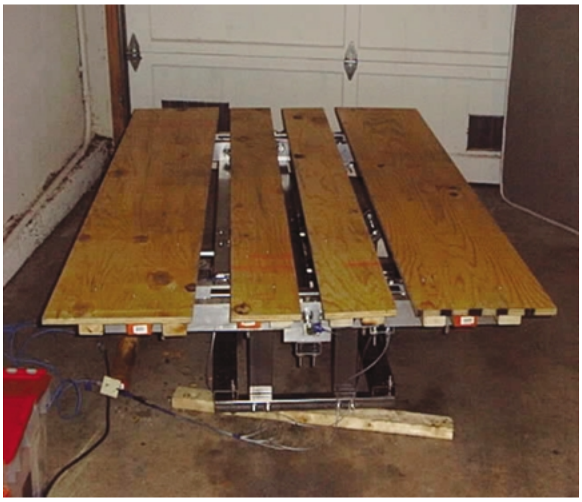


Figure 14. Bed frame with segments in place and horizontal.

A computer-based sound acquisition system was designed and prototyped to detect the occurrence of snoring. The data from the microphone are digitized. The algorithm uses a simple amplitude thresholding to separate loud events from background noise level. If the time intervals between loud events acquired over a certain period of time have a low standard deviation from the mean value, then the sound is considered periodic, indicating the presence of snoring. This algorithm was shown to be effective on simulated sound tracks, but has not been optimized or clinically evaluated for robustness.

To detect the position and posture of the patient, two sensor belts, one for the mattress and one for the chest of the patient, were developed. Both are outfitted with force sensitive resistors (FSRs), 4 on the person's belt and 8 on the mattress belt, and sense the pressure generated by the body of the person on the mattress. Given the characteristic frequency content and intermittent nature of the snoring perturbation on the FSR sensor output, snoring does not have any impact on the ability of the system to detect body position. The person's belt measures the posture of the sleeper, and the mattress belt the lateral location of the sleeper. Together, and in combination with the detection of snoring, the information can be used to actuate the appropriate bed frame segments. The complete Morpheus-Bed with the mattress belt is shown in Fig. 15.

Figure 15. Morpheus bed with mattress, showing also the transverse mattress sensor belt placed under the torso of the sleeper.

Integration of the SleepSmart and Morpheus Designs

Although the two projects, SleepSmart and Morpheus, began as a single, integrated, robotic bed research project at Stanford University supported by Paramount Bed Corporation (Tokyo, Japan), each has had separate paths due largely to the significant amount of development each major robotic function (sensing and actuation) required. Hosei University (Tokyo, Japan) subsequently supported the Morpheus Project while National Trust, Ltd. (Tokyo, Japan) supported the development of SleepSmart. In a future integration of the two projects, the Morpheus sensor belts will be replaced functionally by the mattress pad sensing system of SleepSmart. With the added sensing capabilities, other robotic functions could be incorporated as well, such as the change in ambient room lighting and temperature, based on the sensing of user responses to sleep conditions. It is clear that with the integration of the Morpheus and SleepSmart systems, there are many more opportunities to interact with the sleeping experience and enhance the quality of sleep.

Discussion and Future Directions

While bench testing of the hardware configuration and the major software modules has been completed, clinical testing is needed for both systems to complete the parameterization of the control algorithms. For Morpheus, the timing and graded actuation of the tilting based on snore detection needs to be determined. For SleepSmart, the long-term validity of the breathing and heart rate information has to be established with clinical “gold-standard” instrumentation, and the sleep quality correlation software needs to be populated with a more complete set of daily activity mediators of stress with the collaboration of sleep disorder clinicians.

Conclusion

These two companion projects can together form the basis for a low-cost—relative to clinical instrumentation—home-based consumer product to diagnose and alleviate mild sleep disorders. If used in a physician-supervised program, the data from the combined system can aid the physician-plus-patient team make informed decisions about the proper course of treatment based not only on a single physician visit or a single night of sleep in a polysomnography suite, but on weeks of multifactorial data.

Acknowledgments

These studies were funded by a grant from the Paramount Bed Corp., from the National Trust Corp., and from Hosei University, all based in Tokyo, Japan. Student team members Y. Tai, G. Liu, J. Norman, J. Ford, T. Osada and T. Tabata made critical contributions to the bed prototyping. We are also grateful for the help of Prof. Clete Kushida, MD, of the Stanford Sleep Disorders Clinic, Prof. Ware Kuschner, MD, and James Canfield, BS, CCPT, of the Palo Alto VA Pulmonary Service, Roy Sasaki, MD, of the Palo Alto VA Spinal Cord Injury Service, and Prof. Kos Ishii, PhD, of the Stanford University Dept. of Mechanical Engineering.

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