Enhancing Pilot Performance with a *SymBodic* System

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***Abstract*—Increased fatigue of pilots during long flights can place both humans and machine at high risk. In this paper, we describe our research on a SymBodic (SYMbiotic BODies) system designed to minimize pilot fatigue in a simulated 48 hour mission. The system detected the pilot's sleep breaks and used this information to plan future sleep breaks. When fatigue could not be prevented, the SymBodic system assisted the pilot by providing relevant flight information through a vibro-tactile vest. Experiments showed that it was difficult for the pilot to adapt to the suggested sleep schedule within the duration of the experiment, and fatigue was not avoided. However, during periods of severe sleep deprivation, the SymBodic system significantly improved piloting performance.**

***Index Terms*—human performance, fatigue management, haptic feedback, sleep / wake classification, symbodic, aerospace**

I. Introduction

Solar Impulse is an ambitious project to fly around the world with a solar powered airplane [1]. The project aims to prove the concept of flying over long distances with renewable energies only. Until now, no manned solar powered airplane was able to fly over night. To meet this challenge, a single-pilot, solar powered glider with a wingspan of 63 meters of and a weight of 1500 kg has been developed. The cruising speed has been set to 25 knots. The lack of sleep during a long term flight and the high cognitive demands will increase the pilot's fatigue over time. This is a very challenging environment for the human body and a major question must be raised: How can a human maintain high performance during a sustained flight of multiple days?

In order to minimize pilot's fatigue and to assist in moments of fatigue we introduce here the concept of a *SymBodic* pilot assistance system. A *SymBodic* system (SYMbiotic BODies) is a wearable device that supports symbiotic communication between the bodies of the human and of the machine in order to improve feeling, monitoring and control. The developed *SymBodic* system analyzes relevant body variables of the pilot (heart rate, respiration) in order to provide a dynamically updated physiological profile to the machine and pilot himself. It also analyzes, summarizes, and conveys information from key parts of the machine to the pilot in an ergonomic fashion. The *SymBodic* device is designed to improve the pilot's perception of the machine and to allow the machine to activate alert signals if the pilot sleeps or takes the machine outside safety limits. By suggesting the pilot to sleep in time slots that fit a polyphasic sleep schedule [2] and waking him up accordingly, we expect to be able to minimize total sleep duration, reduce the pilot's overall fatigue, avoid severe sleep inertia [3]. By additionally assisting the pilot with a vibro-tactile vest that provides augmented information about the plane's state we expect to increase the pilot's overall performance.

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II. State of the art

A. Sleep management in sustained operations

Stampi [4] summarized different strategies for sleep management during continuous work as: *1*) Storing sleep in advance; *2*) Enhancing the restorative sleep value; *3*) Continuous 5 hour sleep; *4*) Anchor sleep; *5*) Extending wakefulness with pharmacological agents; *6*) Irregular napping; and *7*) Polyphasic ultrashort sleep. Methods 1 to 4 are not appropriate for long term piloting tasks and the use of pharmacological agents is not desired. Irregular napping during short breaks is the most common way to address sleep loss in continuous work situations. However, it is not guaranteed that enough sleep can be accumulated [4]. There is evidence that dividing the waking day into several regular occurrences of short naps can reduce the wake intervals and the total needed sleep time without effects of sleep deprivation (polyphasic ultrashort sleep) [2]. This sleep-wake behavior is dominant in most animals and is also present during the early development of humans [4]. For these reasons we have chosen to implement a polyphasic sleep schedule planner into the *SymBodic* system.

B. Sleep/wake detection

Traditionally, the states of sleep and wake are classified using the analysis of brain wave patterns (EEG) [5]. Several research groups demonstrated the use of EEG signals for drowsiness detection of drivers [6]. The acquisition of EEG signals shows a major inconvenience: Several electrodes needs to be glued to the scalp and the corresponding wiring to the recording system makes it very cumbersome for a pilot. There is also a high susceptibility to different sources of noise.

Another commonly used technique for sleep/wake discrimination is actigraphy [7]. In actigraphy, the acceleration of the wrist of the subject is recorded and phases of low activity are classified as sleep. However, it is difficult to derive a reliable sleep prediction from the actigraphy signal. As consequence, activities characterized by low levels of motion, to which the pilot will be frequently exposed, are often misclassified as sleep [8].

We have suggested the use of electrocardiogram (ECG) and respiratory effort (RSP) signals for wearable sleep and wake classification [9]. The signals were obtained from wearable sensors that were more comfortable than EEG electrodes. For this reason we integrated a cardio-respiratory based sleep-wake discrimination system into our *SymBodic* prototype.

C. Vibro-tactile piloting aids

Enhancing navigation and environmental awareness with vibro-tactile systems (VTSs) is an intensively studied subject and it has been proven useful when visual feedback is reduced, absent or overloaded [10], [11]. Most VTSs are aimed at providing spatial information to help the user locate himself or his vehicle according to the surrounding environment. The influence of vibro-tactile collision warning signals in driving simulations has been successfully studied [10]. VTSs have also been used for navigation way point enhancement in aerial and naval applications [12] and for enhancing spatial orientation and situation awareness in military applications [13].

For enhancing pilot performance in the simulator, we have previously tested different tactile paradigms for long duration flights [14]. We also implemented a VTS into a vest to provide directional information to the pilot [14]. Components of this VTS have been used for the haptic feedback element of the *SymBodic* system.

III. Method

A. SymBodic device

The *SymBodic* system presented in this paper is composed of four major elements (Fig. 1): *A*) A plane state recording system; *B*) A pilot physiological recording system; *C*) A central processing unit (CPU); and *D*) A haptic feedback with a vibro-tactile vest. The entire system is designed to be non-intrusive, light-weight, and with small energy consumption.

1) Plane state recording: Flight dynamics (roll, pitch and yaw) were recorded with the plane's internal sensors and were sent to the CPU. To test the prototype, we collected the flight dynamics from a realistic flight simulator called X-Plane (Laminar Research, SC).

2) Physiological data recording: The physiological signals ECG and RSP were measured using a commercial available and certified recording system called Equivital (Hidalgo Ltd., UK). This wearable system is composed of a washable belt equipped with 3 dry textile electrodes and a piezo-resistive strain-gauge for the measurement of respiratory effort, and an electronics module for signal acquisition. The signals were sent over a serial Bluetooth wireless link to the CPU.

3) CPU: A PC acquired the cardio-respiratory data and the flight dynamics. The cardio-respiratory data were used for the sleep/wake classification. The classification algorithm was adapted from [9]. Spectral features were extracted with a short time Fast Fourier Transformation from each consecutive 20 second long segment of the the raw ECG and RSP signals. A single layer, feed-forward Artificial Neural Network classified the segments into wake and sleep. If the system detected that the pilot was sleeping longer than the 20 minutes required for

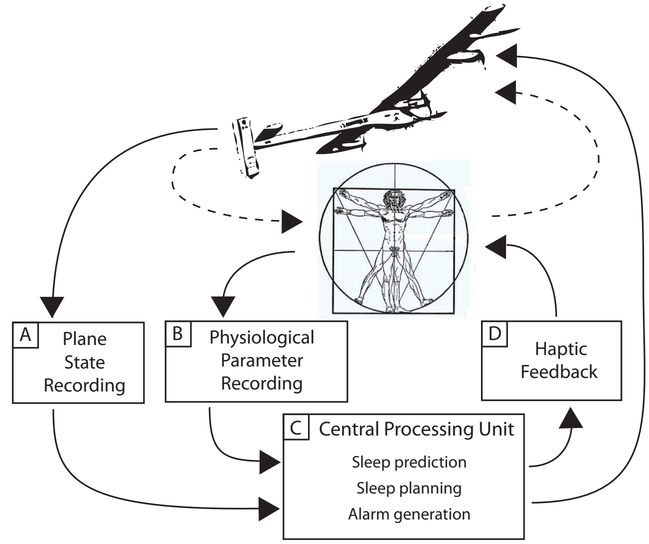

Fig. 1. Symbodic system: A symbiosis between the bodies of the airplane and the pilot is created. A dynamically updated profile of the machine (A) and pilot (B) are recorded and processed (C) and fed back to the pilot with a haptic interface (D) or as information to the machine. The dashed arrows represent the traditional piloting pathways.

the polyphasic sleep, an auditory wake up alarm was generated. The PC also compared the measured flight dynamics to optimal flight parameters that were stored in an internal flight model. A gradient vector proportional to the deviation of the optimal roll angle was computed. When the measured angle was outside of a threshold angle preventing the airplane from going to a slide-slip behavior, a warning signal was generated. Gradient vector and warning signals were sent to the vibrating vest.

4) Haptic feedback: Haptic feedback was provided with a vibrating vest. The vibrating vest was composed of 32 vibrating motors distributed around the torso of the pilot. The actuators were positioned to establish a morphological correspondence between the body of the pilot and of the machine [14]. The maximal intensity of each motor was calibrated with an external application to compensate for the perceptual difference due to variation of skin sensitivity at different body locations. The actuators were activated in two modes: *a*) When the plane was outside of its normal roll angle, all the actuators with a positive gradient value were activated at full amplitude; and *b*) When the plane was inside of its normal roll angle, the actuators were activated with amplitudes proportional to the gradient vector.

B. Experiments

We conducted a preliminary study with one male subject of age 29 to test the *SymBodic* system. The test pilot was in good health, not taking medication and a non-smoker. We obtained written consent from the participant. Two experiments, each of 48 hours duration, were conducted in a full-immersion flight simulator at the Solar Impulse airbase in Dübendorf, Switzerland that incorporated a realistic Solar Impulse plane model.

The first experiment consisted of a control study without the *SymBodic* system where the pilot was responsible for managing his own sleep breaks (irregular napping) and was piloting without haptic feedback. In the second experiment the *SymBodic* system was activated. In order not to bias the pilot's perception, the wearable parts of the *SymBodic* system (recording belt and vibrating vest) were worn in both experiments. The experiments were separated by one week. Both started in the evening at 20:00 and lasted for 48 hours. The subject was asked to arrive at least one hour before the start of the experiments in order to get familiar with the instrumentation, equipments and experiment procedure. The subject was asked to take normal resting nights with at least 7 hours of sleep during the two preceding nights. He was also told not to sleep or nap in the 12 hours before the experiment, which was verified with a sleep diary. The subject was told not to drink alcohol or take caffeine or other stimulants for 36 hours before and during the experiments.

In both experiments, the subject's mission consisted of two consecutive tasks that were continuously repeated. The *flight task* consisted of flying the plane as horizontally as possible for a duration of 30 minutes. During the flight task the pilot could also take his naps by switching on a minimalistic auto-pilot that was able to correct for small trajectory perturbances. When the auto-pilot was off we monitored the roll deviation to evaluate the overall performance of the pilot with and without *SymBodic* system when under sleep deprivation. We computed the mean standard deviation of the roll from the baseline inside a rolling window of 5 minutes duration. To evaluate the efficiency of the *SymBodic* system in improving the reaction time of the pilot, we embedded a reaction-time test into the flight task. Once for each 30-minute flight segment, at random intervals, we introduced an artificial 'wind burst' that would bring the plane instantly to a roll angle of + or - 25 degrees, which was outside of the safe roll zone (± 10 degrees). We evaluated the response time of the pilot by measuring the time between the wind burst event and the stabilization of the aircraft within the safety roll zone. If the pilot did take a nap during the flight task, he could be woken up by either *a*) The alarm signaling the start of the test task; *b*) The alarm that is generated when the plane exceeds the safe roll limits. The alarm was auditory during the control experiment and auditory and vibratory during the *SymBodic* experiment; or *c*) When during the *SymBodic* experiment the system detected that the pilot slept longer than the polyphasic 20 minutes.

The flight task was followed by a *test task* to conduct different tests in order to assess the effectiveness of the *SymBodic* system and that required the pilot's full attention. We tested the vigilance of the pilot using a version of the psychomotor vigilance test (PVT) [15]. Because the available time for the test was limited, we used a shorter 5-minute version [16]. The test was implemented with the open-source Psychology Experiment Building Language (PEBL) framework [17]. From the PVT we extracted the fastest 10% of responses, which provided an estimate of the pilot's best possible reaction time. This is known to be reduced under sleep inertia [3]. Before and after each PVT, the pilot's subjective estimation of his own sleepiness was examined with the Karolinska Sleepiness Scale (KSS) questionnaire [18]. The scale ranges from 1 (extremely alert) to 9 (very sleepy, fighting sleep). The test task lasted 6 minutes. The pilot was allowed to eat and use the bathroom during the test task, occasionally prolonging the task's duration. During the test task the simulation was paused.

The cockpit was monitored with a CCTV infra-red camera. Based on the video recordings a technician determined for the whole experiment if the pilot was sleeping or not. The information recorded during the control experiment was used to calibrate the sleep/wake classifier [9].

We used the non-parametric Wilcoxon (Mann-Whitney) rank-sum test for comparing the data because some of the data did not follow a normal distribution.

IV. Results and Discussion

The total accumulated sleep over time was below the aimed 8 hours in both experiments (Fig. 2). We observed that during the control experiment the pilot accumulated more than 2 hours of sleep debt (difference between cumulative sleep of polyphasic sleep schedule and effective accumulated sleep during the experiment). After the maximal accumulation of sleep debt in the second night, the pilot felt so tired that he required to interrupt the mission and sleep continuously for 2 hours and 20 minutes (starting at 03:42). During the *SymBodic* experiment the pilot was able to stay closer to the planned polyphasic sleep schedule and reduce the total sleep duration by one hour. The KSS values showed that the pilot followed a circadian sleepiness pattern with a maximum low at 03:00 (Fig. 3). There was no significant difference between the control and the *SymBodic* experiments (Wilcoxon $p > 0.90$) which indicated that the pilot did not adapt to a polyphasic sleep schedule. A similar pattern was observed on the fastest 10% of responses of the PVT test that had a more pronounced peak during the second night (Fig. 4). Again, there was no significant difference between the control and the *SymBodic* experiments (Wilcoxon $p > 0.42$). The median of the mean roll angle deviation was significantly higher during the control experiment (Wilcoxon $p < 0.05$), which showed that the pilot kept the plane more stable during the *SymBodic* experiment with the haptic feedback enabled. The *SymBodic* haptic feedback produced the most pronounced improvement during the severe sleep deprived period in the second night (Fig. 5). The time to stabilize the plane after a severe wind burst was significantly reduced in the *SymBodic* experiment (Wilcoxon $p < 0.01$). Again, the effect was most pronounced during periods where the KSS was above 6 (Fig. 6). These findings indicate that the information provided by the haptic interface to the pilot was helpful, especially when the pilot's cognitive skills were reduced. Because only one subject was included into the study, randomizing the order of the experiments was not possible which might have introduced a learning effect during the first experiment. However, a possible learning effect can be ignored in this case, because *a*) The plane stabilization task was simple and a learning effect would have been produced very early during the experiment; and *b*) During the first 6 hours of the experiments, no significant difference in speed of stabilization (Fig. 6) or deviation of roll angle could be observed (Fig 5).

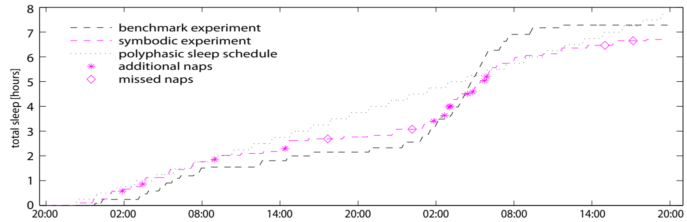

Fig. 2. Cumulative sleep chart. The pilot was able to add 13 additional breaks (stars) and did not follow 4 sleep recommendations (diamonds) during the *SymBodic* experiment.

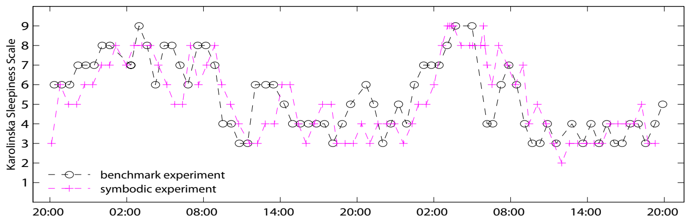

Fig. 3. Karolinska Sleepiness Scale (KSS) questionnaire results. The scale goes from very alert (1) to very tired (9).

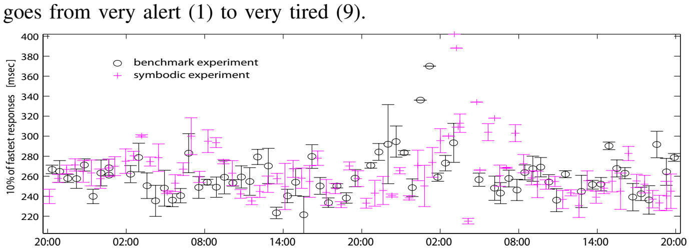

Fig. 4. Mean Psychomotor Vigilance Test (PVT) fastest 10% of responses (length of errorbars cover the SD).

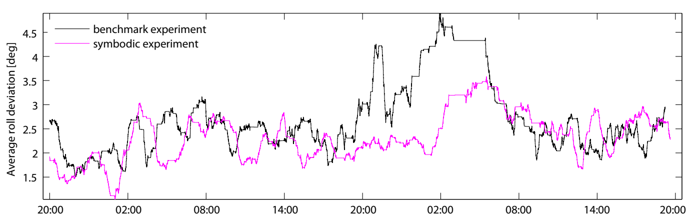

Fig. 5. Mean deviation of roll angle from horizontal plane position.

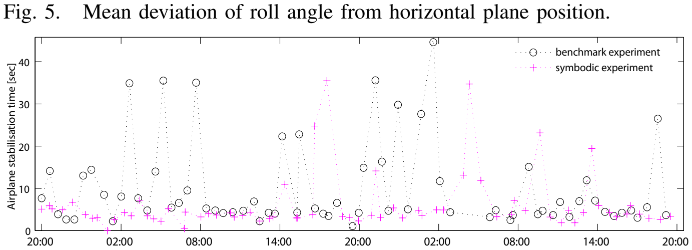

Fig. 6. Speed of plane stabilization after a severe wind turbulence.

V. Conclusion

This study was limited in the number of subjects and it was not possible to randomize the order of the experiment. Therefore, the results cannot be generalized for a larger group of subjects. Despite these limitations we can draw several conclusions on the use of a *SymBodic* system for the assistance of pilots during long missions. We have shown that is possible to provide a polyphasic sleep schedule to the pilot that is based on his previous sleep history. However, adult humans require several days to adapt to a polyphasic sleep schedule [2]. Our experiments were too short for full adaptation and could not show a decrease of the pilot's fatigue with the *SymBodic* system. We believe that the *SymBodic* system could be used for helping the pilot to adapt a polyphasic sleep schedule prior to the mission and then in maintaining it, but this hypothesis will need experimental validation. We also showed that the haptic feedback incorporated in the *SymBodic* device significantly increased the pilot's performance, especially during periods where he was severely sleep deprived. This could be a life saving element in critical situations during long term flight missions where pilots might encounter episodes of increased fatigue.

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