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Development and Evaluation of an Open Source Wearable Navigation Aid for Visually Impaired Users (CYCLOPS)

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Abstract— **A wearable computing navigation aid for the visually impaired was designed, tested and evaluated in a series of pilot experiments. The system comprises an ultrasonic transceiver, a digital compass with a built-in accelerometer, sound playback electronics, a vibration motor and a microcontroller, all integrated inside a glove. The system prototype is power autonomous for about an hour and interfaces with the user through both audio and tactile output. The system design goals were reliability, wearability, power autonomy, an intuitive user interface, and open source architecture, low cost and rapid prototyping. A total of 16 pilot testers participated in evaluation experiments, in which they had to use CYCLOPS (http://cyclops-eye.yolasite.com) to navigate an unfamiliar obstacle course towards a goal destination designated by an audio target. 5 of the pilot testers were visually impaired, and 11 were blindfolded seeing individuals. Post-experiment interviews were used to collect qualitative data from all participants. Results indicate that pilot testers of both groups found CYCLOPS to be intuitive to use for blind navigation, even after a brief 5min familiarization period. Several functional corrections and requirements were extracted from the experimental and qualitative data, which will be used to drive the design of future CYCLOPS prototypes.**

Keywords- biomedical engineering; visually impaired; blind navigation; ultrasonic sensor; ultrasound range finder; digital compass; MEMS accelerometer; ATmega328 microcontroller; vibration motor; tactile output; audio cue; open source; electronic glove; wearable computing; smart clothing; power autonomous; pilot study; obstacle course; qualitative questionnaire

I. INTRODUCTION

The past few decades have seen a rapid increase in microprocessor power and a consequent drop in the cost and power consumption per floating point operations per second [1]. While most of the headlines are grabbed by microprocessor clock-speed champions, a quiet progress of low budget, power autonomous devices in industry and in our daily routines is riding on a wave of inexpensive, power efficient microcontrollers [2].

Such microcontrollers are typically running at much lower MHz clock speeds and are ideally suited for rapid prototyping, proof-of-concept, educational and portable device development. Microchip's PIC (Microchip Inc, USA) and Atmel's AVR (Atmel Inc, USA) microcontroller series are popular examples.

From the medical and biomedical engineering point of view, this increasing variety of inexpensive, power efficient, portable microcontrollers and sensors provide an opportunity to rapidly prototype proof-of-concept multi-sensor data acquisition systems [3]. Such systems are particularly suited to real-time monitoring and data collection from within [4] or around the human body [5], for ubiquitous and wearable computing [6] biomedical applications.

Despite the aforementioned technical advances, the white cane used by visually impaired people for navigation has not been significantly improved. Some efforts have recently been made to add electronics functionality [7] or replace the cane altogether [8, 9], however they have not been widely adopted. A cheap, open source solution that can be improved through crowd sourcing design and assembled by anyone with basic electronics skills has only just become available [10,11].

II. DESIGN AND TESTING

The aim of the CYCLOPS project [10,11] was to design a navigation aid which is truly useful to visually impaired users, whether or not they use a white cane for their everyday movements. Secondary aims were that the device be wearable, inexpensive, open source, possess an intuitive interface and be amenable to rapid prototyping.

A. Design requirements

CYCLOPS had to be wearable and if possible interchangeable among individuals, at least during the prototyping and pilot study stages of development. A glove was selected as the most convenient clothing item to modify for navigation assistance purposes.

Reliability of obstacle detection was the most stringent design requirement. This was defined as the need to reliably and repeatedly detect objects larger than an orange, at a range of 2 meters and within the angle usually swept by the white cane for visually impaired users. This angle is generally less than 45 degrees horizontally and significantly smaller on the vertical axis.

The device had to provide on-demand navigation cues with respect to the points of the compass. A digital compass was selected for this purpose, possessing a built-in accelerometer to compensate for inclination errors. It was decided that measurement error should not exceed 20 degrees. This requirement stems from the risk of providing misleading orientation due to cumulative error between adjacent secondary points of the compass, e.g. north and north-east, which are separated by 45 degrees.

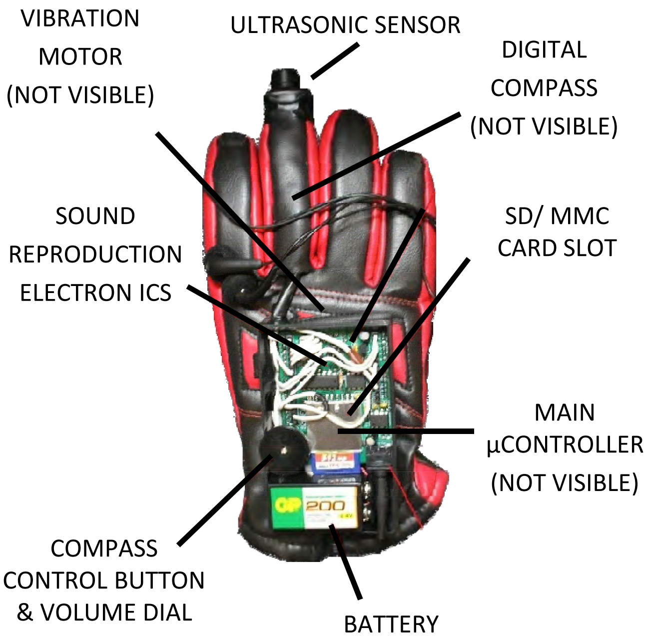

Fig. 1: The CYCLOPS wearable aid for visually impaired navigation, depicted with the electronics compartment open.

The CYCLOPS user interface had to be simple, intuitive and geared towards visually impaired users. Audio and tactile stimuli were selected, giving a user the option of using either or both. Sound output is considered essential in order to allow the device to provide orientation information, as well as system messages (e.g. low battery, power on greeting, keeping the glove horizontal during compass measurement, etc). The user must have the option to disable audio cues and still maintain navigation capability, for discrete use in silent areas such as a library or the theatre.

The device had to possess a minimum of an hour's worth of power autonomy and adopt an open source programming architecture, so that it can benefit from crowd sourcing design improvements.

B. System implementation

Upon considering the design requirements for cost, power autonomy, open source architecture and rapid prototyping, an Arduino Uno microcontroller board was selected as the basis for the first CYCLOPS glove prototype. It contains the Atmel ATMega328 8-bit microcontroller chip which is power efficient at 20MHz and possesses 32kb of programmable on-flash RAM. The assembled system can be seen in the explanatory diagram in fig. 1.

A Maxsonar EZ4 ultrasound transceiver (Maxbotix Inc, USA) was selected as the means for measuring distance, due to its reliability, power efficiency and relative resilience to dust, humidity and ambient light variations. It is complemented by an LSM303DLH digital compass (ST Microelectronics, EU) with a built-in 3D accelerometer, which is capable of compensating for minor inclination errors.

Sound output is produced by a Waveshield sound reproduction board (Adafrruit Inc, USA), which is capable of playing back pre-recorded MP3 and WAV audio files stored on its detachable SD memory card. Tactile output is produced by a small vibration motor scavenged from a mobile phone.

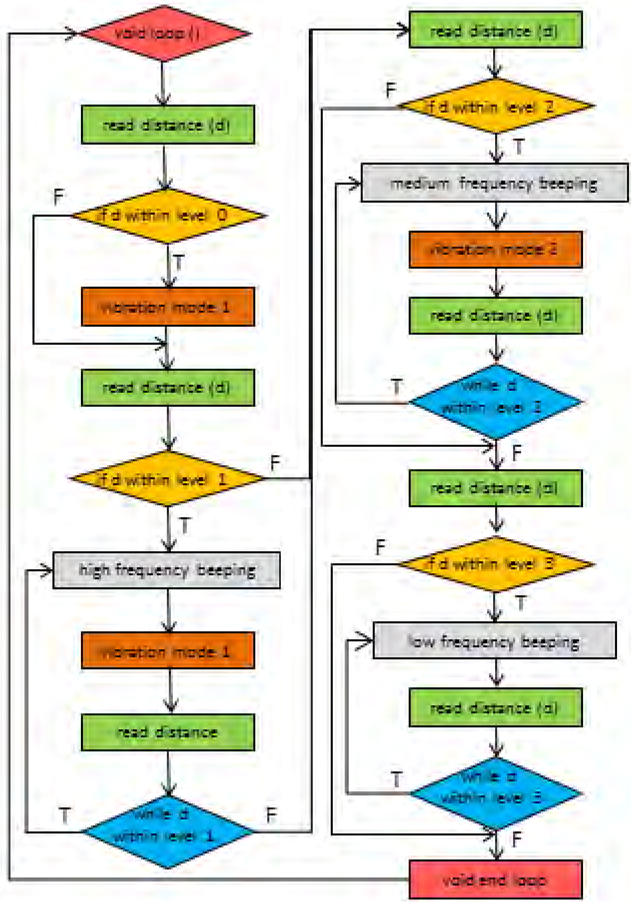

Fig. 2: High level flow chart of the main code loop running on the microcontroller. Levels 0-3 are sets of parameters defining distance zones in which detected objects are classified.

The first prototype device is fitted inside a plastic skiing glove and is powered by a 9V battery. The glove is large size to fit most users' hands and all wiring is concealed inside. User input is accepted via an on-off switch, a volume control dial and a button to request a compass reading. Tactile output is provided through the vibration actuator and audio output through the speaker or 3.5mm earphone jack.

C. Testing and characterization

The limits of CYCLOPS's object detection and ranging capabilities were tested through a series of experiments. Initially, a piece of cardboard was presented and measurements obtained to estimate linearity. Results are presented in fig. 2. Objects further than 5m were not consistently detected, hwile closer than 30cm they were detected in a non-linear fashion. Even though the full advertised range of the ultrasonic sensor (6.45m) was not validated, the system far exceeded the 2m range that was set as a design requirement.

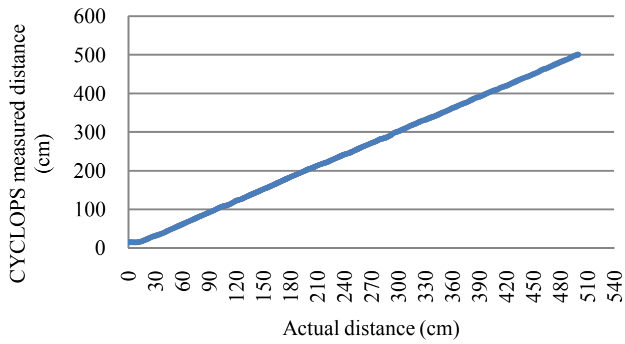

Fig. 3: Distance measurement accuracy of the CYCLOPS glove. Integration of the Maxsonar EZ4 ultrasonic range finder into the glove appears not to affect linearity. Error bars are invisible in this scale.

The 5m range meant that the software had to be adjusted for indoor use, otherwise the device would provide disconcerting output due to the incessant detection of wall surfaces. Obstacle detection warnings were organized in four levels:

- Level 0: 0 – 0 .3m, dire audio warning, vibration
- Level 1: 0.3 – 1m, audio warning, staccato vibration
- Level 2: 1 – 1.5m, audio notification
- Level 3: 1.5 – 2.0m, audio notification

Audio notifications between levels varied in pitch and volume.

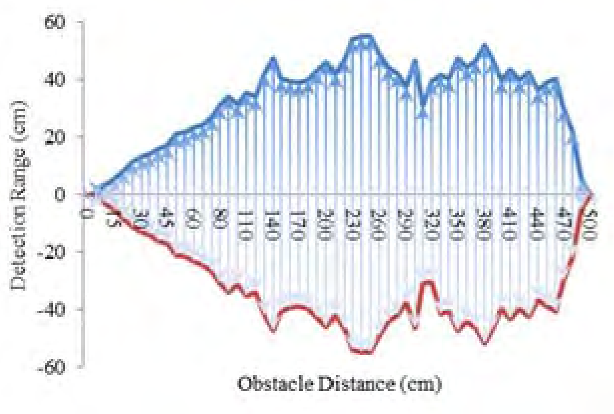

Fig. 4: Detection range funnel of the CYCLOPS glove. The distance of the detected object is represented by the x-axis. The y-axis represents the distance of the object from the axis running along the glove finger at the end of which the transceiver is mounted.

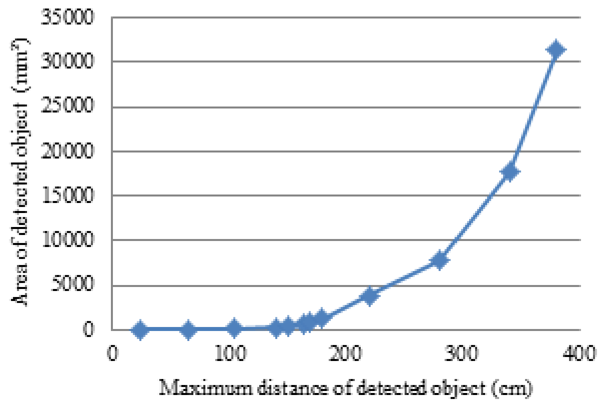

Fig. 5: Maximum distance (x-axis) at which objects of variable surface area (y-axis) can be reliably and repeatedly detected. The objects used for the experiment were cardboard discs of various diameters. Data points generated averaging multiple measurements.

The CYCLOPS glove's angle was consequently detected. A large piece of cardboard was moved in front of the glove and then shifted sideways, until it was no longer detected. The results from this experiment are depicted in the chart of fig. 3.

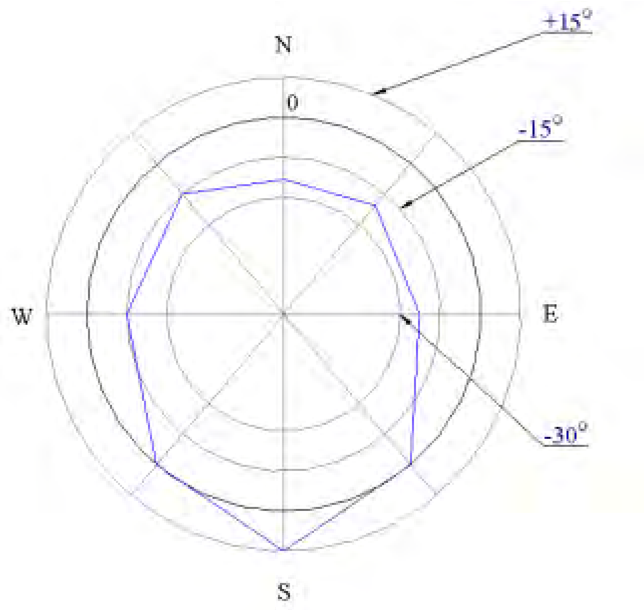

Fig. 6: Average measurement error of the CYCLOPS compass output (polygon loop) versus a more accurate magnetic instrument. Each concentric circle represents a 15 degree deviation between the two instruments. Error distribution is skewed due to the proximity of other electronic or metal components, particularly the vibration motor.

The detection funnel for CYCLOPS which corresponds to the range of the white cane used by visually impaired people (approximately 1.5m), was found to have an angle of 42 degrees. This is wider than a typical sweeping angle for the cane, without moving one's wrist. The relevant design requirement was therefore satisfied.

An additional experiment was devised to test the CYCLOPS object detection sensitivity at different ranges. The developers aimed to find out the smallest detectable object at different ranges. Cardboard discs of different diameters were constructed and placed on the axis directly in front of the device. They were then moved away until they were no longer reliably detected. If an object was detected consistently 10 times, it was considered that it can be reliably detected at that distance. Results from this experiment are presented in fig. 4. CYCLOPS can detect both moving and static objects, however extracting movement speed and directional information is all but impossible with this particular singe sensor hardware setup.

The digital compass's performance as part of the CYCLOPS system had to be evaluated for precision, particularly since it was inevitable that it be placed in close proximity to other electronic components. The software was adjusted so that no compass reading would take place while the vibration motor was in operation.

Fig. 5 is a chart depicting compass error, as compared to a more accurate mechanical instrument. Experimentation took place in an open space with no metal objects nearby. Despite a conscious design effort to distance the compass from other components within the CYCLOPS glove, measurement error was found to be skewed. Still, it satisfied the design requirement of less than 20 degree error.

III. PILOT STUDY EXPERIMENTS

In order to evaluate and better understand the adaptability of users to the CYCLOPS audio and tactile interface, a small scale preliminary pilot study was planned. Two groups of volunteer pilot testers were formed, one composed of 5 visually impaired (4 men, 1 woman) and the other of 11 seeing individuals (9 men, 2 women).

The members of the visually impaired group had an average age of 30.4yrs and a age range of 20-45, while the seeing group had an average age of 30.9yrs and a range of 16-54. The combined age average for both groups of pilot testers was 30.8 and the range 16-54.

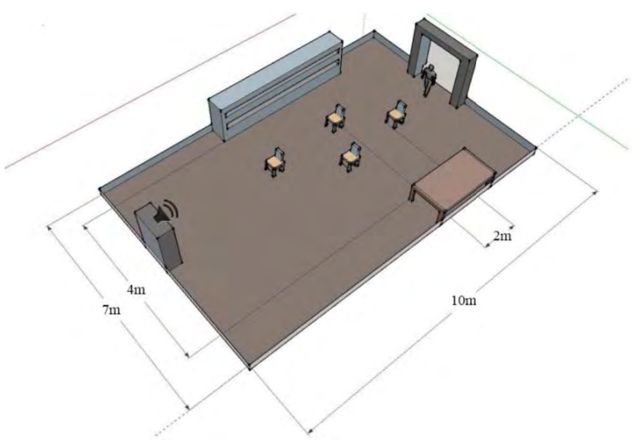

Fig. 7: Diagram of the obstacle course navigated by the pilot testers using the CYCLOPS glove.

The pilot testing experimental protocol was structured, consistent and involved a 3-phase procedure. During phase 1, the testers were introduced to CYCLOPS using a pre-determined script which was read out to them by the interviewer. They were then allowed 5 minutes to put on the device, ask questions and experiment with detecting nearby objects (seeing volunteers were not blindfolded at this stage).

During phase 2, they were blindfolded and taken to a different room, where an obstacle course had been set up. The length of the course was 10m and involved making one's way around 4 obstacles towards a device playing an audio cue. Details of the obstacle course set up are presented in Fig. above. The obstacle course was set up in the premises of the Thessaloniki School for the Blind, in Thessaloniki, Greece.

The 3rd and final phase, the pilot tester's blindfold was removed and they were interviewed in a semi-structured way for approximately 5 minutes. The interviewer went through a structured set of questions and proceeded to initiate a few minutes of free discussion, in which the pilot tester was encouraged to informally express their opinion about CYCLOPS, ask questions, point out short-comings and suggest ideas for future improvement.

IV. RESULTS & DISCUSSION

The main aim for conducting the pilot study was to gauge user reactions and understand their adaptability to the CYCLOPS interface. All 16 pilot testers completed the obstacle course successfully and spoke about CYCLOPS in a positive way afterwards, despite having a deliberately short period of time to get accustomed to its interface.

One of the hypotheses being tested was that the visually impaired group would have an advantage, possessing extensive experience building mental navigation maps without visual input. The seeing group, on the other hand had to adjust to the temporary loss of vision, the sense they most heavily rely on for building mental navigation maps on a daily basis.

Another factor that was deemed of investigative interest was each tester's familiarity with electronic devices which require at least rudimentary technology interface skills. The interviewers focused in particular on the number of such devices and their frequency of use in the tester's daily routine. The hypothesis was that the more familiar the testers were the quicker they would be to pick up the skills required to efficiently navigate around obstacles using CYCLOPS.

Fig. 7 is a chart of the average index of familiarity with electronic devices for each group, as self-assessed by each pilot tester. Five is the maximum grade and represents a person who has multiple electronic devices that they use constantly in their daily routine. Zero represents a person who hardly ever uses electronic devices.

On average, the visually impaired group assessed themselves as significantly more familiar with electronic devices in their daily routines (4.40 vs 3.64 out of a possible 5.00). As was expected from an urban population relying on the use of TV remotes, mobile phones and personal computers, all but 3 of the 16 pilot testers assessed themselves at grade 3 or higher.

Fig. 8 shows the average time it took each group to traverse the obstacle course. Among the visually impaired group, some use a white cane for navigation and some do not. There was no obvious correlation between cane use and obstacle course traversal time.

Despite having an overall higher technological familiarity index and experience in navigating without visual cues, the visually impaired group required 16 seconds longer than average to complete the obstacle course. This was a counter-intuitive and thus unexpected result.

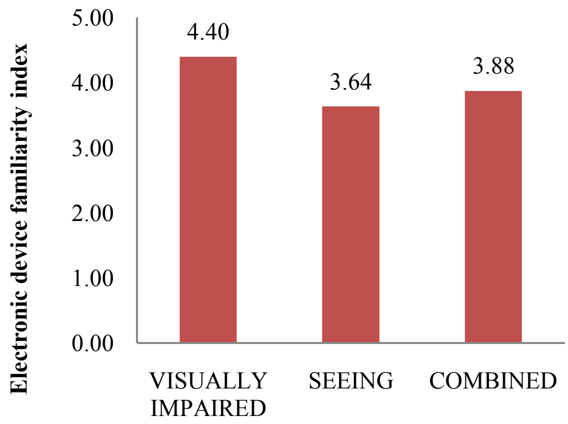

Fig. 8: Pilot testers' self-assessed familiarity with electronic devices in their daily routine (0 = not familiar, 5 = extremely familiar).

One possible explanation is that this result is due to the low number of pilot testers and would change once results from a more extensive pilot study are obtained. Another possibility is that the brief period of familiarization affected pilot testers in the two groups differently: seeing individuals may have obtained more information about CYCLOPS functionality during the 5-miunute familiarization period than their visually impaired counterparts. Both explanations can be tested straightforwardly through further experimentation.

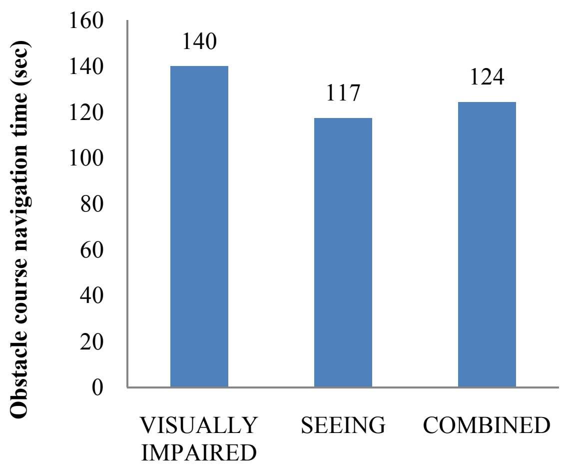

Fig. 9: Average navigation time required by the two groups of pilot testers to traverse the obstacle course using the CYCLOPS glove, after familiarizing themselves with it for 5 minutes. Seeing individuals were blindfolded during navigation but not during the familiarization period.

It is worth noting that an individual who was neither a developer nor an interviewer, traversed the obstacle course in dramatically less time than any of the pilot testers. He did however have the chance to see CYCLOPS in action several times and had a visual mental map of the obstacle course, since he was the cameraman who filmed the experiments. For this reason, his performance data was excluded from the pilot study results. Still, this incident indicates that longer practice periods with the CYCLOPS prototype are likely to make a significant difference in a user's efficiency in navigation and obstacle avoidance.

Compared to the standard white cane navigation aid for the visually impaired, the CYCLOPS glove appears to fit as a complementary type of tool. A properly balanced comparative experiment was not possible to perform, since all available white cane users had lifelong experience using it and only 10 minutes of experience using CYCLOPS. Still, the time required to cross the obstacle course in most cases was less than a quarter, suggesting that a combination of the two tools might provide the optimum choice for most user needs. For instance, CYCLOPS can be designed to work alongside the white cane: when speed is of the essence, the two devices can be used in conjunction, CYCLOPS contributing distance sensing information and the white cane contributing speed and accuracy. In scenarios where discrete exploration of space is required, or when a less conspicuous solution is desired, the user can retract the white cane and navigate using the CYCLOPS glove alone.

V. CONCLUSIONS & FUTURE WORK

The CYCLOPS navigation aid was designed with a focus on wearability, intuitive user interface, low cost and open source programming. The first prototype design exceeded all initial design requirements. Quantitative and qualitative data obtained from the evaluation experiments indicate that pilot testers adapted to CYCLOPS quickly and that their performance increases dramatically the more time they practice. The data also contains multiple suggestions for improvements, as well as new functions. Future prototypes are planned to be more accurate, more tightly integrated, have a user-adjustable detection range, improved audio interface, increased power autonomy and cost less. There are also plans for a step counting, data logging and gesture recognition functions.

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