INSPEX

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***Abstract*—The INSPEX H2020 project main objective is to integrate automotive-equivalent spatial exploration and obstacle detection functionalities into a portable/ wearable multi-sensor, miniaturised, low power device. The INSPEX system will be used for 3D real-time detection, location and warning of obstacles under all environmental conditions in indoor and outdoor environments with static and mobile obstacles. Potential applications range from safer human navigation in reduced visibility conditions, small robot/drone obstacle avoidance systems to navigation for the visually/mobility impaired, this latter being the primary use-case considered in the project.**

Keywords— surrounding perception, spatial exploration, integrated system, embedded, low-power, portable, wearable, health

I. Introduction

In recent years, obstacle avoidance systems for (autonomous) vehicles has been a hot research topic. These systems combine multiple sensing technologies (e.g. LiDAR, radar, IR and visual) to detect different types of obstacles across the full range of possible lighting and weather conditions. The data from these sensors are fused and combined with vehicle orientation (e.g. from an Inertial Measurement Unit (IMU) and compass) and navigation subsystems. These systems are typically large and heavy, and not fully integrated in a unique system. They are power hungry and require large computational capabilities. They are indeed limited to high-end vehicles and robots. Moreover, having GPS and/or IMU based traditional navigation systems is not enough to ensure safe navigation of users. Basically, knowing the exact user location in a highly smart IoT environment is not sufficient to avoid unmapped static and dynamic obstacles under all conditions of visibility.

The objective of INSPEX, a H2020 funded project, is to make obstacle detection capabilities currently implemented in high-end vehicles available as a personal *portable*/*wearable multi-sensor*, *miniaturised*, *low power* device. The INSPEX *spatial exploration system* will be used for *3D real-time* detection, location and warning of obstacles under *all environmental conditions in indoor and outdoor* environments with static and mobile obstacles. Potential applications range from safer human navigation in reduced visibility conditions (e.g. for firefighters), small robot/drone obstacle avoidance systems to navigation for the visually/mobility impaired.

INSPEX will integrate its smart spatial exploration system in a regular white cane for the visually impaired and provide 3D spatial audio feedback to the user on obstacle location. This use-case VIB use-case is considered highly demanding in terms of miniaturisation, integration challenges, power efficiency and needs for communication with the smart environment.

The choice as primary use-case for a smart white cane may have societal impacts. Actually, According to the World Health Organization statistics (WHO), 285 million people are visually impaired world-wide [27]. Note this the number is expected to double by 2040, due to aging and health diseases. Among these VIB people, only 5% are fully autonomous in their daily mobility. This lack of autonomy has partly its origin in the lack of confidence the person has in his/her mobility capabilities, and efficient use of the white cane. Electronic white canes, able to detect obstacles on the whole person height should improve VIB confidence in their mobility capabilities.

Fig. 1. INSPEX main objective.

The paper is organized as follows. Section III summarises the main objectives and challenges INSPEX will tackle. Section III provides an overview of the related work while section IV gives a first attempt of architecture for the INSPEX system. Section V summarises the INSPEX vision.

II. INSPEX Objective and Challenges

To put it in a nutshell, INSPEX main target is to integrate automotive-equivalent spatial exploration and obstacle detection functionalities into a wearable/portable device (Fig. 1).

This global objective breaks down in several challenges to be solved: -

1. it requires the *integration of several range sensor technologies* (i.e. LiDAR on chip, MEMS ultrasound, Ultra Wide-Band (UWB) Impulse Radar). Basically, each sensing technology compensates for drawbacks of the other ones [1] to detect obstacles of various types in different conditions. Actually, one technology is not able to provide the all-conditions functionality;
2. a processing unit will be integrated in the INSPEX spatial exploration system to fuse the sensor data and *build the Occupancy Grid (OG) environment model*. An OG is a spatial partition of the external world into a set of cells [2]. Each cell contains the occupancy probability, i.e. the probability to find an obstacle at the cell location. To get a more robust and accurate estimation of the cell state, several sensors are fused through the Multi-Sensor Fusion (MSF). Standard MSFs use Bayesian fusion [3] or evidence combination [4] that require floating point computation. Unfortunately, such implementation is too power costly to be integrated in a portable device. Basically, the OG calculation must be highly efficient for the INSPEX system to meet its integration constraints (low power consumption, accuracy, cost and reliability);
3. the portable/wearable INSPEX system will be immerged in connected environments. As a consequence, it must provide *connectivity to smarter environments* and become part of the IoT. Context-aware communication capabilities will provide the user with a collaborative fabric of smart objects, giving the ability to determine the context of moving objects and to dynamically blend user experiences;
4. a *stringent power management strategy* must be implemented to fulfil the system lifespan in terms of energy autonomy. This will be achieved by dynamic adaptation of the number of range sensors used as a function of the available energy, which will imply adaptation at run-time of the obstacle perception algorithm, and as a function of the environmental conditions (e.g. lighting/visibility conditions), providing context-aware autonomous reconfiguration. This power management strategy will be verified using *formal methods* to ensure its proper design and functioning;
5. the INSPEX system will experience similar use environments to mobile communications devices. Its reliability must be taken into account right at the design phase (*design-for-reliability*). It will be designed to function under various weather conditions (e.g. rain, snow, sand) over a large temperature range (typically -20°C to 40°C) but also in low visibility conditions (e.g. night, dust, smoke, fog);
6. the architecture will be *modular* for the system to address several application domains;
7. INSPEX first demonstrator targets the VIB (Visually Impaired and Blind) community (see Fig. 2), and field tests will be conducted. As a consequence, *ethical issues* must be considered. Moreover, the INSPEX system being a connected device, privacy concerns must be addressed right at the design phase of the system (*privacy-by-design*).

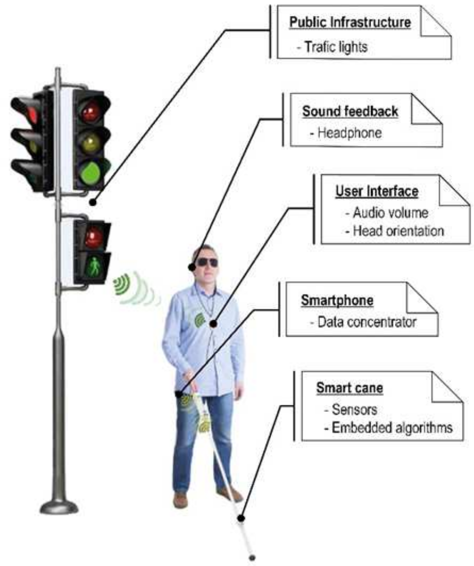

Fig. 2. INSPEX initial demonstrator.

Note that the VIB use-case is seen highly demanding in terms of miniaturisation, integration challenges, power efficiency and needs for communication with the smart environment. The INSPEX system should not exceed **200gr** in weight and **100cm^3** in volume. **10 hours of lifetime in continuous use** are expected with an initial target for power consumption smaller than **500mW**. Information regarding the location of obstacles will be provided *via* an extra-auricular sound feedback via Augmented Reality 3D Audio interface, taking into account the attitude of the user head to improve the navigation experience by a better obstacle localisation and warning.

III. Related Work

INSPEX main advances will cover miniaturisation and optimisation of sensors to cope with the targeted requirements provided above. Software must be carefully integrated in order to decrease as much as possible its own power consumption. Targeting VIB as primary use-case, the INSPEX system must truly answer user needs, and offer robustness and reliability for the user to trust the system outputs. Lastly, cost may be a strong driver for system adoption.

This section now reviews these different facets of INSPEX.

A. Range Sensing in all-conditions

It is well known (e.g. [20] and references therein) that obstacle detection systems based on ultra-sonic range sensors suffer from limited useful range (typically, < 3 m) and difficulties of operating on highly reflective surfaces. Laser-based solutions do not suffer from these limitations, but they can be highly sensitive to ambient natural light and have difficulty identifying transparent or mirror-like surfaces. RF Radar range sensor performance is affected by the electromagnetic backscattering characteristics of the obstacle, namely its Radar Cross Section (RCS). The RCS of any obstacle is very different from its mechanical response (i.e. to ultrasound waves) or optical response (i.e. to LiDAR). Ref. [21] shows that the UWB radar can be used effectively to detect and avoid obstacles through precipitation (rain, snow) and adverse environmental conditions (fog, smoke), thus being fully complementary to LiDAR which is inefficient in such conditions. Typically, RF Radars operating at 8GHz are not sensitive to clothes and light shadowing conditions and can “see” behind such short range obstacles, whereas ultra sound and LiDAR sensors will need mechanically or optically unobstructed conditions to operate. In a nutshell, Ultra Sound, RF Radar and LiDAR are complementary technologies since bringing diversity in obstacle backscattering intensity. Moreover, they offer different trade-offs in terms of range, power consumption, directivity and packaging constraints. As a consequence, their co-integration will offer the all-condition functionality targeted by INSPEX.

Unfortunately, systems with all-visibility capability that combine visual, IR, LiDAR, radar and/or ultrasonic sensors are confined to large (autonomous) vehicles, large Unmanned Aerial Vehicles or lab prototypes with small autonomy [5], all these applications being able to cope with the high weight, computational load and power budget required for long-range 3D obstacle detection [6, 7]. No miniaturised, light-weight, low-power solution that integrates all the range sensing technologies targeted by INSPEX (LiDAR-on-chip, MEMS ultrasound, Ultra WideBand Impulse Radar) exists that is suitable for use in the consumer domain for wearable/portable navigation of people, small robots or drones. Two factors contribute to this lack: the size and power budget of existing individual sensors; and the challenges of multiple sensor integration [8].

Much of the research activity in the area of wearable/portable obstacle detection has been done in the context of assistive technology for the VIB community [9, 10], drones [11, 12] and robotics [13], and assistive mobility for people with disabilities [14]. However, no solution offers the all-conditions functionality with the size, weight and power consumption consistent with a portable/wearable device.

B. Sensor Data Fusion and Occupancy Grid Calculation

Fusion algorithms will fuse the data from, and manage the uncertainties of, the heterogeneous set of range sensor technologies in order to ensure detection of various obstacles (size, shape, material, and colour) in 3D, at different heights and ranges and in all environmental conditions, see Fig. 3.

Many solutions already exist in the literature with pioneer works in [3, 4]. However, the approaches traditionally implemented in OG calculation require to manipulate probabilities. As a consequence, they require floating-point arithmetics. Real-time MSF computation with a growing number of cells and sensors is challenging. To accelerate MSF, parallel implementation in GPUs [15, 16] or many-core platforms [17] have been proposed. All these attempts use floating-point representation for probability estimation and fusion. Unfortunately, requiring floating-point support hinders the integration of OG-based MSF on highly constrained embedded platforms. The implementation of OG-based MSF should instead make use of integer computation [18] as much as possible to decrease the power consumption associated with data treatment.

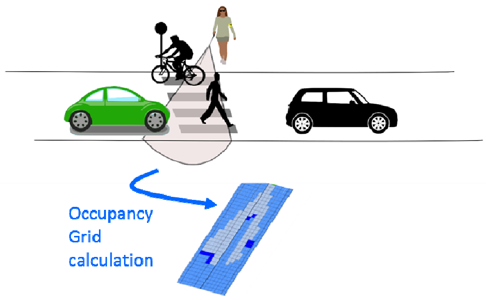

Fig. 3. Detection of obstacles with heterogeneous range sensors and Occupancy Grid obtained by data fusion.

C. Reliable Smart Navigation for People with Special Needs

Navigation for people with special needs (e.g. VIB people, person in a wheelchair [19]) is not easy at all in the so-called smart cities as cities are mainly planned for sighted persons. Integrating obstacle detection and appropriate feedback together with communication with the smart city in their daily life devices (e.g. white cane, wheelchair) will improve their mobility experience and get people integrated back into society.

To detect a large variety of obstacles (in size, shape, colour, materials), the smart navigation system must embed a *mobile detection device* that integrates several range sensing technologies in order to improve the performance of obstacle detection, each technology compensating for the drawbacks of others.

Most of today smart white canes only integrate ultrasound technology, either for commercial products (e;g. [22, 23]) or in research prototypes (e.g. [20, 4]), sometimes together with other range sensors [15]. Most of these references do not report power consumption figures, nor system lifetime. Moreover, their exploration range is usually quite limited (less than a few meters). These factors have also limited a widespread adoption of ultrasound solutions in other portable devices such as tablets and smartphones. On the other hand, the growth of the Internet-of-Things vision pushes Industrials to develop new sensors, actuators and smart devices smaller, more versatile, lower cost, and more power efficient. In this frame, it is clear that proximity sensor for wearable electronic devices would benefit from small and low power features

Other solutions based on cameras can also be found (see e.g. [26]). However, image processing presents computational cost (and therefore power consumption) that is not consistent with the INSPEX objective of developing a low power device. Moreover, acceptability of the horseshoe-shaped device proposed in [26] that sits around the user’s shoulders will have to be demonstrated.

Navigating in a city is far from safe for VIB people. Even if regulations force architects, city planners and builders to design the city to make it accessible to VIB people, sooner or later, they sustain injuries (especially on the head and chest) due to unexpected obstacles, thus decreasing their confidence in their autonomous mobility capabilities [28]. Electronic white canes offer an answer because they detect in advance obstacles, not only on the ground, but also over the whole person height, thanks to the range sensor(s) they integrate. However, they do not properly perform in all weather conditions because they integrate a unique range sensor technology for price and power consumption reasons (see Fig. 4). Moreover, as they integrate a unique range sensor technology, they cannot detect all the various obstacles (in shape, size, colour, and material) a person will encounter. As a consequence, even if mobility with an electronic white cane offers safer navigation, it is currently far from fully safe.

D. *Affordability of smart white canes*

Affordability is one of the adoption drivers. Fig. 4 shows the price of several commercial products. The cheapest one, Smart Cane, integrates ultrasonic sensing. Mini Guide, Palm sonar, K-sonar, Ultra Cane and Mowat are also based on ultrasound range sensors. The most expensive electronic cane integrates a LiDAR.

Thanks to technology advances and integration breakthrough, it will become possible to integrate several range sensing technologies in a small size low power device. Moreover, as these range sensors will target the consumer market, their price should decrease, leading to an integrated smart exploration system with a cost aligned with the price of today products that possess a unique sensing technology.

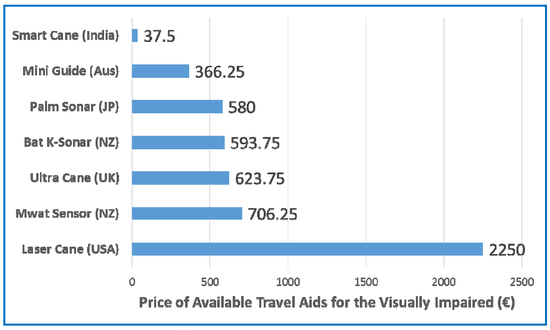

Fig. 4. Smart white cane affordability [27]

IV. Architecture First Attempt and Review of Main Submodules

Integrating in a white cane the INSPEX system offers tremendous challenges in terms of integration, miniaturisation and power management. Actually, the available energy is naturally constrained by the batteries embedded in the system. This requires a stringent optimisation on the various parts that constitute the INSPEX system. Second, the user cannot bear a heavy system nor accept an ugly one, pushing constraints on the integration aspects (size and form factor, weight) even further. Moreover, the system reliability is very important for the user to trust the smart white cane. Lastly, cost has also strong impact on system adoption.

A. *Archtechture overview*

The spatial exploration system developed in INSPEX for the VIB use-case is made of three devices, namely the (A) *Mobile Detection Device*, the (B) *Mobile Device*, and the (C) *Audio Headset Device*, see Fig. 5. Each device will be split in several submodules and components that must be rigorously developed, taking into account their own allowed power requirements and size constraints.

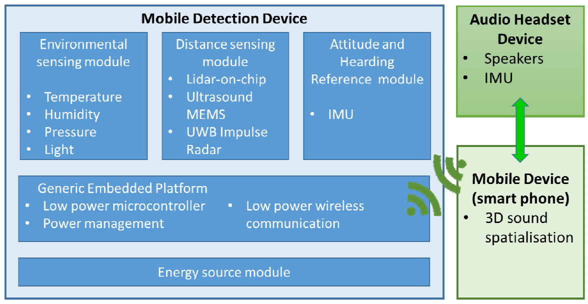

Fig. 5. INSPEX smart integrated system architecture (first attempt).

The *Mobile Detection Device* will integrate the different range sensing technologies in order to fully cover the person height, and search "far away" the potential dangerous obstacles (e;g. those moving towards the user with "fast" speed, taking into account the maximal speed of the user). Fig. 6 shows the expected coverage of the range sensors that will be integrated in the INSPEX smart spatial exploration system.

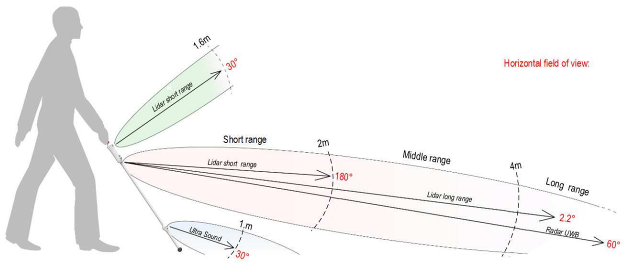

Fig. 6. Coverage of the different range sensors integrated in the white cane

Low power context aware communication capabilities will also be integrated. Actually, the OG calculation will be embedded within the *Mobile Detection Device* integrated in the cane. Therefore, the data throughput required between the cane and the *Mobile Device* worn by the user is compatible with Bluetooth Low Energy which is currently the best off-the-shelf solution in terms of power consumption and interoperability with the different operating systems (Android, iOS, Windows mobile). Thanks to its Internet connection, the *Mobile Device* can also offer new services to the user of the INSPEX system by allowing it to access remote point-of-interest databases and navigation services [29].

The exploration system will come with the *integration of software* in the hardware to make it truly *smart*. INSPEX will make use of a co-development approach of the practical system, together with its formal modelling and verification. Key to this is the identification of the system properties whose verification gives the most added value to the development as a whole, especially regarding to its reliability and stability. Identifying such properties will make clear which kind, or kinds, of formal approach is/are best suited to the task. A significant impact on the practicability of different verification approaches comes from the limited computational resources that the lightweight (not only in mass but in energy consumption) INSPEX architecture can support. Although it may decrease the fidelity of environment representation that is possible, it thereby also decreases the verification burden, in that only less complicated computations need to be modelled and verified.

Formal modelling and verification will help improve the safety and security of the functionality of the whole INSPEX system, including the reliability of context aware autonomous reconfiguration associated with the context-aware power manager. This latter will autonomously adapt which sensors will be used by the fusion algorithm, depending on the amount of energy currently available (e.g. some sensors might be no more supplied because they are too power hungry) and on the environmental conditions (e.g. some sensors might be no more supplied because they badly behave in these conditions).

B. Review of main submodules developped in INSPEX

The INSPEX partners bring four state-of-the-art range sensors to the project, namely, a MEMS ultrasound sensor, a short range large field of view LiDAR-on-chip, a long range narrow field of view LiDAR, and an UWB RF radar. The choice for these range sensing technologies is conducted by the capability of the final system to detect a large variety of obstacles (in shape, size, material, and colour) in different environmental conditions (temperature, humidity, luminosity, visibility) and particular situations (holes, stairs). Their organisation will allow the full coverage of the person height to better alarm the user on potential dangers, included at the head height (see Fig. 6).

INSPEX will miniaturise and reduce the power consumption of these sensors to facilitate system integration and meet its requirements in terms of power consumption, size and weight of the global system. Indeed, an initial review of the envisioned architecture showed that the sensors taken from the partners without any modification, possess a too high power consumption. These range sensors will then be integrated with an IMU, environmental sensing, signal processing and power efficient data fusion techniques embedded on a low power microcontroller, wireless communication, and user interface, all in a miniature, low power system designed to operate within wider smart/IoT environments.

1) MEMS ultrasound sensor

MEMS ultrasonic transducers (MUT) are used in many applications, such as non-destructive testing (NDT), speed sensing, collision warning (‘sonar walking’), automation, flow metering (Doppler) and medical imaging. There are two types of MUTs, based on their actuation mechanism: capacitive MUTs (CMUTs) and piezoelectric MUTs (PMUTs). PMUTs have a lower power consumption than CMUTs, which can require a polarization voltage of around 200V. PMUTs are based on either bulk piezoelectric ceramic (with poor acoustic coupling to air or liquids) or on piezoelectric thin films (PZT, AlN) allowing them to be integrated into MEMS technology. When arrays of the latter are formed, ultrasound transducers allow the technology limits of conventional bulk ones to be overcome. 2D array MEMS transducers can be miniaturised to produce real-time proximity signals. Moreover, by using pulse-echo Time-of-Flight techniques, ultrasonic MEMS can work over 1m distances with sub-mm ranging accuracy. In INSPEX, a piezo membrane MEMS (PMUT) together with its driving ASIC [30] will be optimised and integrated in the system.

2) LiDAR-on-chip

Thanks to the huge market of the smartphone and the embedded camera, small size and low power LiDAR are, and will be in the very near future, the best candidates for the autofocus (AF). Range and bandwidth are compatible with the VIB use case that targets obstacle detection within a range less than 1 meter (short range), and within a range of a few meters (3 to 5, long range). Such a technology is compliant with low power and low size requirements. INSPEX will optimise two LiDARs brought to the project by partners. The first one will be a Long range LiDAR with a field of view of 2.2°. Currently the prototype has been demonstrated with a range of up to 21m [31]. This is a single channel laser and the objective is to reduce the size by developing a chip based solution for the electronics. In conjunction with the miniaturization of the single channel module in order to increase the field of view, a 64 channel array version will be developed using the same electronics platform as will be used for the single channel version. The second LiDAR is a short range LiDAR with a large field of view based on an off-the-shelf component. Currently this commercial on-chip sensor allows to look at a single point in the range of up to 2m and is designed for camera auto-focus solutions. Nevertheless a fully footprint compatible second generation will be developed and integrated in INSPEX. This sensor is looking at 9 independent measurement points with a field of view of 30° and a range of up to 3m. It will allow faster scanning of the near proximity with increased spatial resolution for obstacle detection.

3) Ultra WideBand RF radar

Integrated CW or FMCW RF radars for presence detection already exist in the field of e.g. domestic security on the one side and for obstacle detection in the automotive domain on the other side. In domestic security, the requirement being to detect a presence, a large scale variation of the electromagnetic echo strength is enough to get sufficient detection probability. Such limited bandwidth Doppler radars hardly provide precise range information useable in dynamic obstacle tracking systems. In the automotive field, obstacle detection radar, usually operating at 24 or 77GHz, are optimised for performance (range, angle), at the expense of higher cost, high directivity and power consumption of more than 500mW [32]. UWB RF radars have also been successfully applied in healthcare applications, especially for respiration rate estimation of static humans. In such application, sensitivity to very small movements is the key specification, but the measurement range is not adapted to (moving) obstacle detection needs. Smart white cane solutions integrating an RF Radar do not exist today at product level. At R&D scale, one can only find early demonstrators like in [21, 32]. The objective to integrate a UWB RF radar sensor in the INSPEX system with performance of 20m sensitivity range. It will have up to 100Hz refresh rate for high performance tracking of moving targets, 15cm range resolution, 60° azimuth aperture, coarse angle of arrival estimation, and approx.. 100mW of power consumption? The form factor will be compatible with integration in a white cane.

4) User feedback

Many current electronic white canes use haptic feedback (vibration) on obstacles. However, this is limited in its ability to convey complex information, can lead to desensitisation and cognitive overload [34]. Other canes give audio feedback via earphones using audio tones that vary in frequency depending on obstacle distance. While this permits richer and more intuitive obstacle information, it demands too much user attention and distracts from the ambient sounds that VIB people especially rely on to be safe while moving and, again, imposes cognitive overload. To benefit from the intuitiveness and the capacity of audio to convey rich information, but without these drawbacks, the INSPEX system will rely on an Augmented Reality Audio system. That uses an extra-auricular pair of earphones and binaural spatialisation algorithms, the user hearing virtual audio from an obstacle. Efforts will be put to take into account the user's head orientation with respect to the position of the obstacles located on their path.

V. Summary

INSPEX will develop a spatial exploration and obstacle detection system that will provide today automotive functionalities into a wearable/portable device. Several range sensing technologies will be integrated, and their measurements fused to build an occupancy grid, in order to offer all-conditions capability. Augmented reality audio feedback, taking into account the user's head position will inform the user on potential dangers. Different submodules will be optimised to make the system consistent with its own requirement. As primary use-case, the INSPEX system will be integrated in a regular smart white cane. Tests in laboratory and in real-life conditions will be conducted in order to evaluate the system capability.

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