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Evaluación experimental del sistema de teleoperación LiCAS para aplicaciones de robótica aérea y de servicio en base fija

Alejandro Suarez[1,*], Anibal Ollero[a]

[a]*Escuela Tecnica Superior de Ingenieros, Dpto. Ingenieria de Sistemas y Automatica, C/ Camino de los Descubrimientos, s/n, 41092 Sevilla, España.*

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Resumen

Este artículo presenta la evaluación experimental de un sistema de teleoperación cinestético desarrollado para la realización de tareas de manipulación diestra con dos brazos robóticos en aplicaciones aéreas o de base fija, tales como operaciones de mantenimiento en entornos industriales, o la recogida y entrega de paquetes en escenarios logísticos. El sistema consta de una pareja de brazos antropomórficos de muy bajo peso con capacidad de acomodación mecánica (LiCAS) en configuración maestro-esclavo, de tal forma que los movimiento aplicados por el usuario humano en el maestro se replican articulación por articulación al robot esclavo, resultando en una interfaz natural e intuitiva que facilita la transferencia de las habilidades de manipulación entre el humano y el robot. El muy bajo peso de los brazos robóticos (1 - 2.5 kg) hace posible su integración en plataformas multi-rotor de medio tamaño y su fácil despliegue en cualquier escenario de interiores o exteriores. Las capacidades del sistema de teloperación LiCAS han sido evaluadas con una placa de prubeas para manipuladores industriales, así como en una operación de manipulación aérea.

Palabras clave: Robots manipuladores, Robótica aérea, Teleoperación, Tecnología robótica, Soporte a trabajador humano.

Benchmarking the LiCAS dual arm teleoperation system for aerial and ground service robotic applications

Abstract

This paper presents the experimental evaluation of a kinaesthetic teleoperation system developed for the realization of dexterous bimanual manipulation tasks in aerial or ground service applications such as maintenance operations in industrial settings, or in aerial parcel grasping and delivery in logistics scenarios. The system consists of a pair of lightweight and compliant anthropomorphic dual arm manipulators (LiCAS) in leader-follower configuration, in such a way that the motion commands applied by the human user on the leader dual arm are replicated joint by joint in the follower dual arm, resulting in a natural and intuitive interface that facilitates transferring the human manipulation skills to the robot. The very low weight of the robotic arms (1 – 2.5 kg) makes possible their integration in medium scale multi-rotors and the fast deployment in any indoor/outdoor scenario. The performance of the LiCAS teleoperation system is evaluated with a Task Board used for benchmarking industrial manipulators, as well as in an aerial manipulation operation.

Keywords: Robots manipulators, Flying robots, Teleoperation, Robotics technology, Human operator support.

1. Introduction

In the design and development of robotic manipulators intended to conduct operations traditionally carried out by human workers, it is desirable that the robot is able to provide a certain level of dexterity, accuracy, agility, and ability of accommodation to the environment, arising two main technological and research challenges. On the one hand, the robotic arms should provide human-like manipulation capabilities in order to replicate in a natural way the realization of different tasks that in many cases require the use of two arms Smith et al. (2012).

*Corresponding author: asuarezfm@us.es

Several dual arm robotic platforms have been developed, such like the DLR Rollin Justin Borst et al. (2009) and the hand-arm system Grebenstein et al. (2011), the ARMAR-6 Asfour et al. (2019) from the Karlsruhe Institute of Technology, the KITECH dual arm robot Lee et al. (2016), the BAXTER robot, and other industrial manipulators like the ABB Yumi or the Yaskawa SDA. However, the high cost and safety concerns of these robots associated to their relatively high weight have typically constrained their adoption in environments shared with humans, particularly in domestic domains. On the other hand, the integration of the robotic manipulator in non structured environments to conduct non repetitive tasks that cannot be solved autonomously makes necessary the implementation of some learning mechanism to teach the robot how to execute a task from demonstrations Asfour et al. (2008); Billard and Grollman (2013). The survey in Ravichandar et al. (2020) identifies three groups of methods: kinesthetic teaching, teleoperation, and passive observation. Some particular solutions include physical contact between the human user and the robot Yang et al. (2015), using haptic devices Ju et al. (2014), or visual human pose estimation Zimmermann et al. (2018).

The aerial robotic manipulation field Ollero et al. (2021), aiming to conduct operations involving physical interaction with objects or the environment on flight in workspaces that cannot be accessed by ground robots, is significantly challenging due to the strong constraints associated to the aerial platform in terms of limited payload capacity and flight time, dynamic coupling with the manipulator, lack of positioning accuracy, or aerodynamic interactions that do not occur with ground robots. The research and development of this technology in last decade Khamseh et al. (2018); Ruggiero et al. (2018); Mohiuddin et al. (2020) has been motivated by the interest in reducing the time, cost, and risk in the realization of inspection and maintenance tasks Suarez et al. (2022) in scenarios such as power lines, oil and gas refineries Ollero et al. (2018), and others Ollero et al. (2021); Mohiuddin et al. (2020). The relatively low payload capacity of multi-rotor platforms Hamandi et al. (2021), typically in the range of few hundreds of grams or few kilograms, made necessary the development of very low weight robotic arms that are suitable for their integration in this kind of platforms, taking into account the aforementioned requirements. As identified in Ollero et al. (2021), the variety of manipulators that can integrated in the aerial platform is wide, from simple rigid links or grippers, to dexterous dual arm manipulators with compliant joints Suarez et al. (2018b,a). Similarly to ground robots, when the complexity of the aerial manipulation task is too high to be conducted autonomously, it is necessary to take benefit of the cognitive capabilities of human workers through convenient interfaces that allow to control the robot in a natural and intuitive way Suzuki et al. (2022). In this sense, kinesthetic teleoperation systems in leader-follower configuration as the one considered in this work are suitable for aerial manipulation operations.

The LiCAS (Lightweight and Compliant Anthropomorphic Dual Arm Systems) Robotic Arms LiCAS (2021) is an initiative derived from our previous work in aerial robotic manipulation Suarez et al. (2018b,a) intended to increase the technology readiness level (TRL) and explore the possible applications of this kind of robotic manipulators, taking benefit of their three main features: 1) very low weight for easy transportation and integration in multi-rotor platform, 2) mechanical joint compliance for safer interactions with the environment, and 3) anthropomorphic kinematics for natural replication of the human motions. The human-like kinematics allows the realization of complex bimanual manipulation tasks on flight Suarez et al. (2022), but also in ground workspaces. In order to evaluate the performance of this kind of robots, it is necessary to define specific benchmarks Suarez et al. (2020) that also account for the human-robot interface used to teleoperate the manipulator.

The main contribution of this paper is the experimental evaluation of the LiCAS dual arm teleoperation system depicted in Figure 1 in two conditions:

- Using the industrial Task Board described in So et al. (2022) for benchmarking industrial robotic manipulators in fixed base.
- In a parcel grasping and drop operation carried out using a dual arm aerial manipulation robot flying in an indoor testbed.

The system consists of a pair of lightweight and compliant anthropomorphic dual arm manipulators (LiCAS) in leader-follower configuration, implementing a kinaesthetic teleoperation scheme in which the joint references of the follower (LiCAS A1) are obtained from the servo encoders of the leader dual arm (LiCAS AC1) moved by the human user. The paper describes the developed system and presents experimental results in the two mentioned conditions.

Figura 1: Experimental evaluation of the LiCAS dual arm teleoperation system with the industrial task board (left, up) and in an aerial manipulation tasks involving the grasping and delivery of a parcel (left down, right).

The rest of the paper is organized as follows. Section 2 describes the developed system, whereas Section 3 details the evaluation procedure. Experimental results are presented in Section 4, providing some conclusions in Section 5.

2. System Description

2.1. LiCAS Teleoperation System

The teleoperation system evaluated in this work consists of two LiCAS (Lightweight and Compliant Anthropomorphic Dual Arm Systems) in leader-follower configuration, as shown in Figure 2. Each arm provides four degrees of freedom (DOF) for end effector positioning, three at the shoulder and one at the elbow, in the following rotation sequence (see Suarez et al. (2018a) for the detailed derivation of the kinematic model of these arms):

- Shoulder flexion/extension.
- Shoulder abduction/adduction.
- Lateral/medial rotation.
- Elbow flexion/extension.

Wrist orientation joints are not incorporated in order to reduce the total weight and inertia of the arms, and because these joints are not necessary for the intended operations. The main specifications of both arms are indicated in Table 1.

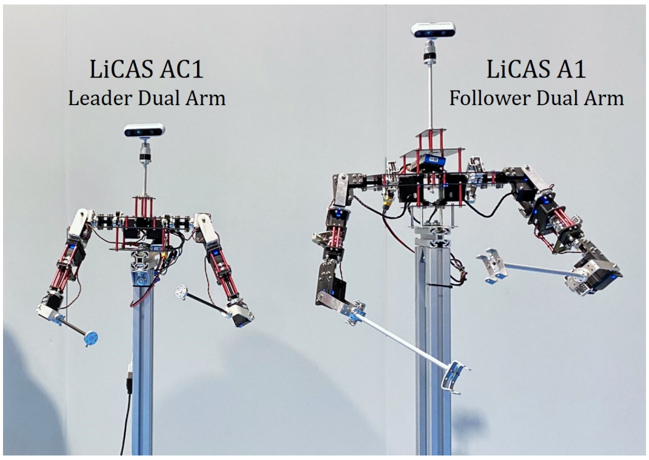

Figura 2: Lightweight and compliant anthropomorphic dual arm system (LiCAS) models AC1 (left) and A1 (right).

Tabla 1: Main features of the LiCAS AC1 and LiCAS A1 manipulators.

		LiCAS AC1	LiCAS A1
Weight	$[kg]$	2.5	1.0
Max. payload	$[kg]$	0.25	0.7
Upper arm link length	$[mm]$	200	275
Forarm link length	$[mm]$	200	275
Arms separation	$[mm]$	250	360
Power supply	$[V]$	7.4 - 9	12 - 16
Compliant joints		No	Yes

The arms are built with Herkulex smart servo actuators and a very low weight frame structure manufactured in carbon fiber and aluminum, designed to protect the servo actuators and support the spring-lever transmission that provides mechanical compliant in all joints Pratt and Williamson (1995); Suarez et al. (2018a). The LiCAS AC1 (leader dual arm) will serve as kinesthetic interface for the human user, using the encoders of the servo actuators for obtaining the joints position that serve as reference for the corresponding servos of the LiCAS A1 (follower dual arm). The mapping of the motion is done joint by joint. In order to allow the user moving the leader arm joints, the torque control of the servo actuators is disabled, so the user only has to compensate a small friction due to the gearbox. The LiCAS AC1 is supported by an aluminum structure such that the shoulder structure is slightly below the user's shoulder so the teleoperation pose results comfortable, as depicted in Figure 1. The LiCAS A1 will be installed in either another support structure for the fixed based benchmark tests, or integrated in the multi-rotor aerial platform for the aerial parcel grasping and drop test.

2.2. *System Architecture*

The components and architecture of the LiCAS teleoperation system are represented in Figure 3. The arms consist of a series of smart servo actuators connected in daisy chain through serial interface to the computer where the control program is executed. The Ground Control Station (GCS) laptop executes four programs: 1) the GCS Operation Code interface used by the user to specify the task to be executed by the LiCAS AC1, 2) the LiCAS AC1 control program that implements the desired functionalities of the leader dual arm and handles the communications with the servo actuators through serial interface, 3) the GCS Operation Code interface for the LiCAS A1, and 4) the LiCAS A1 control program that implements the manipulation functionalities of the follower. Note that, for the aerial manipulation setup, this program is executed in the onboard computer, using UDP (user datagram protocol) sockets and a SSH (secure shell) session to launch the program from the GCS laptop. The software architecture of the arms, described in Suarez et al. (2018a), has been developed in C/C++.

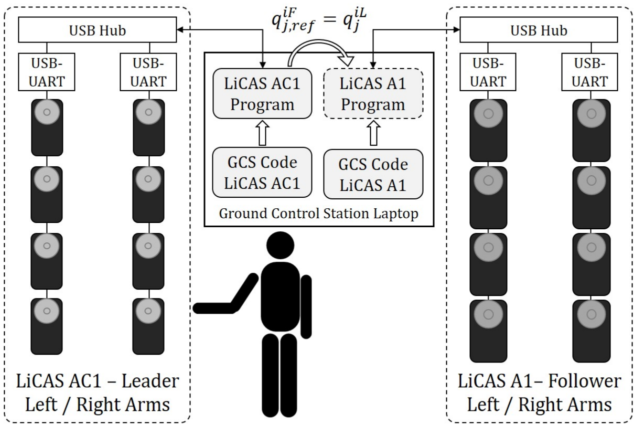

Figura 3: Components and architecture of the LiCAS dual arm teleoperation system. The motions of the human user are captured by the LiCAS AC1 (leader) and replicated joint by joint by the LiCAS A1 (follower). The dashed line in the LiCAS A1 program indicates that this is executed in the onboard computer of the aerial platform.

As mentioned before, in the kinesthetic teleoperation mode, the torque control of the LiCAS AC1 servos is disabled, so the user can easily move the joints for replicating the motion in the LiCAS A1. The LiCAS AC1 control program reads the current position of all the joints of the arms at 50 Hz rate, sending a data packet with these measurements through a UDP socket to the LiCAS A1 control program, where the teloperation task is executed. Exploiting the velocity over-ride mode of the servos to achieve smooth motion tracking Suarez et al. (2018b), the angular position reference of the LiCAS A1 servos corresponds to the position measurements obtained from the leader dual arm, updated also at 50 Hz.

2.3. Aerial Platform

The LiCAS A1 manipulator has been integrated in a medium scale quadrotor platform based on the Tarot X4 frame, providing 4 kg maximum payload and 5 - 10 minutes flight time with the arms. The flight controller consists of a Pixhawk 2 autopilot running the Arudcopter firmware, implementing a position-attitude cascade control scheme. A picture of the platform integrating the robotic arms is depicted in Figure 4. The flight experiments are conducted in the GRVC Aerial Robotics Laboratory indoor testbed, using an Opti-Track positioning system for obtaining the position and orientation of the platform. A simple hook-like gripper is integrated as end effector of the arms for grasping the parcel or any other object with a handle.

Figura 4: Multi-rotor platform integrating the LiCAS A1 dual arm manipulator used to conduct the aerial grasping of a parcel in a logistics scenario.

3. Experimental Evauation

3.1. Task Board Benchmark

The LiCAS dual arm teleoperation system has been evaluated using the task board described in So et al. (2022), showing in Figure 5 the experimental setup in which the human user drives the LiCAS AC1 (leader) to command the LiCAS A1 (follower) motion, having direct visual feedback of the executed operation. This consists of six phases: 1) pushing the blue button, 2) moving the slider to match the display mark (up and down), 3) opening the door, 4) inserting the probe, 5) closing the door, and 6) pushing the red button. The evolution of the test can be followed in Figure 6 and Figure 7, indicating the main events and phases of the task. The left arm arm executes the start/stop button and the linear potentiometer tasks, whereas the door opening has to be done using both arms since the small door handle and the effect of gravity that tends to close the door makes necessary to hold this with the left arm while the right arm pushes forwards the door to open it. Then the right arm, equipped with an electric probe, performs the contact check and closes the door.

As it can be seen, the benchmark is completed in less than 60 seconds. Qualitatively, the door opening phase required significant level of dexterity compared to the others, whereas the electric probe test involved a positioning accuracy below 5 mm. The video of the test can be seen in YouTube (2023).

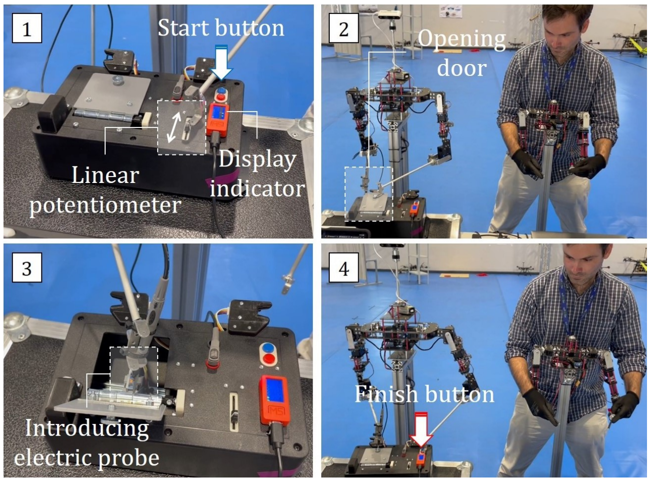

Figura 5: Benchmark evaluation of the LiCAS dual arm teleoperation system with the Task Board.

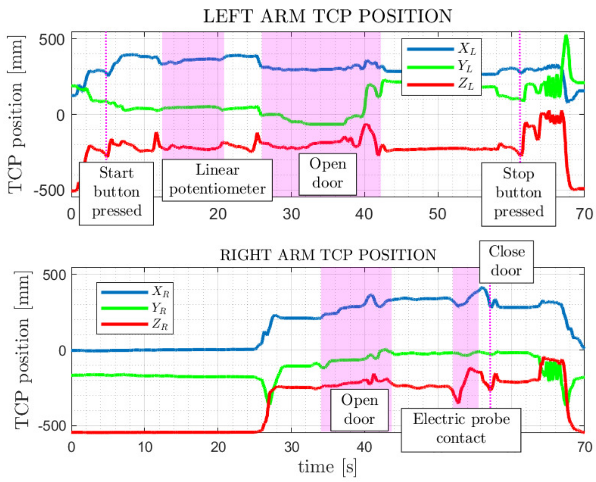

Figura 6: Tool center point (TCP) position of the left and right arms during the execution of the task board benchmark, indicating the main events: pushing start button, sliding linear potentiometer, opening door (bimanual operation), introducing electric probe in contact point, and pushing finish button.

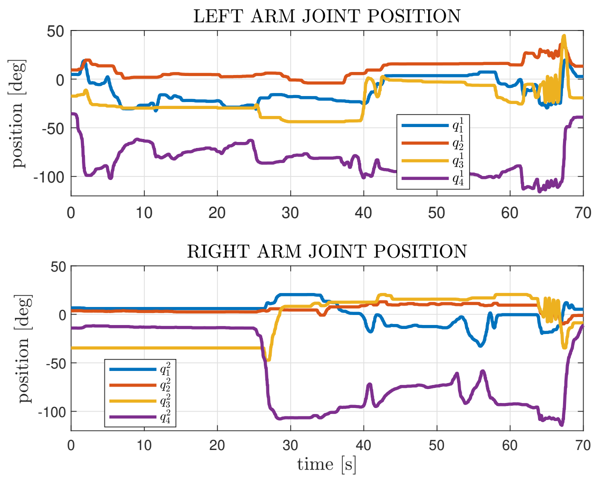

Figura 7: Left and right arms joint position of the follower dual arm (LiCAS A1) during the execution of the task board benchmark.

3.2. Aerial Parcel Grasping and Drop

The goal of this experiment, illustrated in Figure 8 and inspired in the object grasping benchmark described in Suarez et al. (2020), is to assess the ability of a human worker to conduct a parcel grasping and drop operation on flight with a dual arm aerial manipulator using the LiCAS teleoperation system. The operation consists of five phases: 1) the aerial manipulator takes off and approaches to the supply point where the target parcel is stored, 2) the human operator retrieves the parcel from the handles, 3) the aerial platform flies to the drop point, 4) the user drops the parcel in a box, 5) the aerial platform flies back to the landing point. The object to be grasped is a standard DHL Express parcel (size 4), modified to incorporate an aluminum handle in order to make the grasping maneuver more easy (see the end effector of the arms in Figure 4), adding a 0.5 kg payload inside to prevent that the parcel moves away due to the aerodynamic downwash effect introduced by the multi-rotor. The human operator stands inside the testbed in the Ground Control Station where the LiCAS AC1 is located, at 4 - 5 m distance from the shelf that stores the parcel. The evolution of the aerial platform during the realization of the experiment is shown in Figure 9, representing in Figure 10 the trajectory of the left arm (the right arm is not shown since it is almost the same).

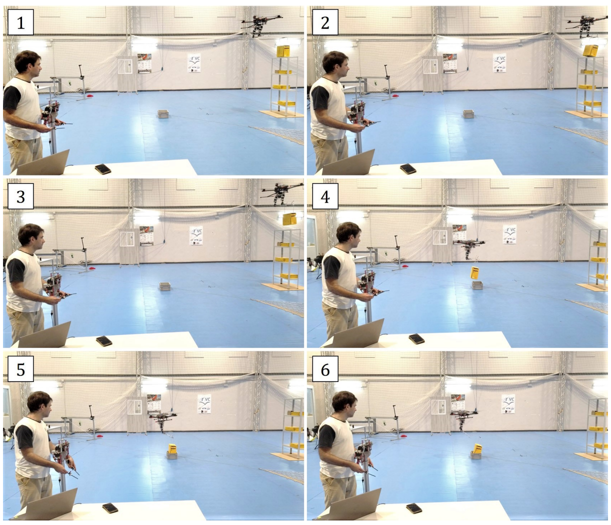

Figura 8: Sequence of images from the video of the experiment showing the aerial grasping of a parcel stored on a shelf and its drop in a box using the LiCAS teleoperation interface. (1) Approaching to parcel with arms retracted; (2) Grasping parcel from handle; (3) Lifting parcel; (4) Approaching to drop box; (5) Parcel dropped in; (6) Arms release.

The main difficulty in the realization of the operation is associated to the point of view of the human user with respect to the flying manipulator and the parcel, since there is a certain loss of perception at distances above 3 m. The aerial manipulation operation also involves the coordination between the pilot and the operator of the arms, taking into account that the multirotor has to be close enough to the parcel so the handle is within the reach of the arms. In order to increase the effective reach, the operator should adopt a retracted pose with the arms so these can be extended around 20 or 30 cm to grasp the object and compensate the displacement of the aerial platform. In any case, the LiCAS teleoperation interface results comfortable and intuitive, requiring no particular training to be used.

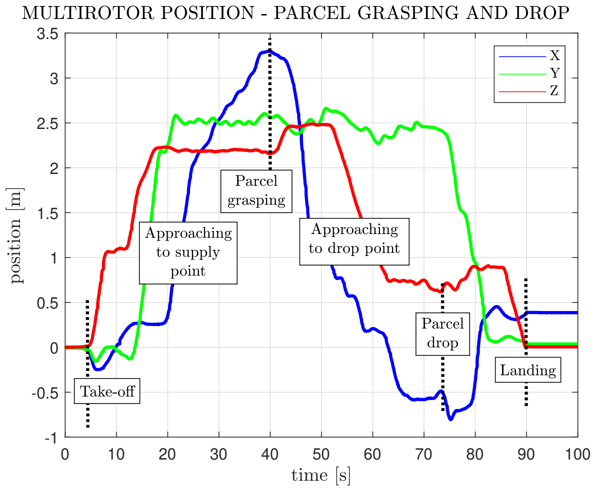

Figura 9: Evolution of the multi-rotor position during the execution of the parcel grasp and drop benchmark, indicating the main phases.

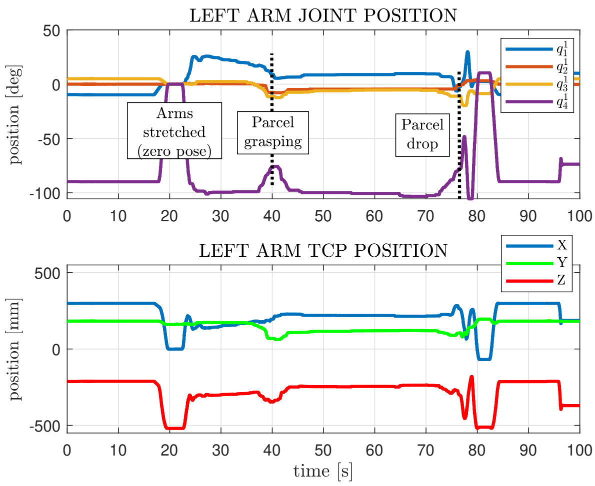

Figura 10: Evolution of the left arm joint and tool center point (TCP) position during the parcel grasping and drop.

4. Conclusion

The LiCAS teleoperation system presented in this work has been proven to be an effective solution for conducting dexterous manipulation tasks in diverse scenarios and situations, either in ground or aerial operations. The very low weight of the arms (1.0 kg the LiCAS AC1, 2.5 kg the LiCAS A1) facilitates its transportation and deployment in aerial platforms to conduct inspection and maintenance operations in difficult access workspaces such as power lines, whereas its human-size and human-like kinematics results particularly suitable for its adaptation to environments shared with human workers.

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