Development of mobile indoor flight test rig for VTOL UAV application.

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Abstract. Vertical take-off and landing (VTOL) Unmanned aerial vehicles (UAVs) significantly contribute to various industries, such as agriculture, geospatial mapping and logistic services. The flying condition of this type of drone is affected by various factors, such as wind disturbance and battery performance. It should be in stable condition to achieve full performance during operation. Flying condition monitoring ensures efficient, high-quality, and reliable operation. Prediction of flying health conditions will reduce catastrophic failures that may cause severe damage, prolonged downtime, harmful incidents, and loss due to higher repair costs and major maintenance services. The rising complexity of VTOL UAV maintenance mechanisms necessitates smart diagnosis and prediction systems. This paper describes the design and implementation of a mobile flight test rig for indoor monitoring VTOL UAV flying conditions using motion detection systems. The primary aim is to utilise motion signals captured from the monitoring setup to develop an intelligent VTOL UAV fault detection and identification system using machine learning algorithms. The emergence of machine learning techniques and signal processing methods exposed research opportunities for constructing high-accuracy learning algorithms for smart VTOL UAV flying health diagnoses. Comprehensive utilisation of massive flying data will increase the accuracy of the learning algorithm, significantly reducing unnecessary maintenance tasks and the high cost of corrective maintenance.

Keywords: VTOL UAV; indoor flight test rig; motion capture camera system; OptiTrack; Motive Tracker; MATLAB

1. Introduction

Unmanned aerial vehicles (UAVs) equipped with Vertical Take-Off and Landing (VTOL) capabilities have recently gained significant attention due to their versatility and potential applications in various industries, including military, civil aviation, and urban transportation [1]. These vehicles offer the advantage of vertical take-off and landing, high manoeuvrability, and efficient use of space, making them ideal for challenging and confined environments. VTOL UAV technology has improved significantly in recent years, focusing on enhancing their performance, stability, and ease of operation [2]. Advanced sensors and control algorithms have improved VTOL UAVs' accuracy and reliability, making them easier to control and track in challenging indoor environments [3]. Advanced research on materials and manufacturing techniques enable the development of lighter and more compact VTOL UAVs suitable for indoor applications [4]. However, testing and validating the performance of VTOL UAVs can be a complex and challenging task.

In the past, outdoor testing has been the standard approach for evaluating VTOL UAVs. However, this method has limitations, including dependence on weather conditions and exposure to environmental factors that can negatively impact test results. Additionally, outdoor testing can also be limited by safety considerations and access to appropriate test facilities [5]. Moreover, traditional outdoor testing methods for UAVs have limitations due to weather conditions, environmental factors, and limited access to suitable facilities [6][7]. Considering these challenges, there is a growing need for an indoor flight test rig that can provide a controlled and safe environment for testing VTOL UAVs.

This project addresses these challenges by designing and developing a mobile indoor flight test rig for VTOL UAV applications. The test rig will incorporate a motion-capture camera system to monitor flight movement and enable performance analysis from real-time flight data. Appropriate testing and validation of the systems are required to design reliable and safe recording areas with massive data recording [8]. An indoor flight test rig would allow for reliable testing of VTOL UAVs under various operating conditions and provide valuable insights into their performance [9]. An indoor test environment also allows for fine-tuning control algorithms and sensors within a controlled environment for precise data collection and thorough analysis [10]. The rigs will also help researchers and engineers better understand the challenges and limitations of VTOL UAVs in indoor environments [11].

In this project, we design and develop an indoor flight test rig that integrates a motion-capture camera system. The motion-capture camera system will enable real-time monitoring of flight performance and provide accurate data for analysis and reporting. The mobile flight test rig will be designed to capture different flight scenarios and conditions and will provide a controlled environment for testing and validating the VTOL UAV's flying conditions. The data recorded from the flight test rig will provide valuable insights into the performance of VTOL UAVs and advance our understanding of their behaviours under different operating conditions [12]. This integrated system will enable the simulation of various flight scenarios, assessment of stability and control, and optimisation of design and performance. Indoor flight test rigs provide a controlled environment for testing and evaluating VTOL UAVs flying performance.

2. Research Methodology

Figure 1 shows the experimental flight test rig setup with a motion capture system involving several components. These include a PC equipped with Motive 2.3.7 software connected to an OptiTrack hub, motion capture cameras, a remote control transmitter, and a quadrotor VTOL UAV attached with a suitable number of reflective markers. The Motion Capture System was calibrated and positioned correctly to ensure accurate data capture and avoid interference from sunlight and infrared.

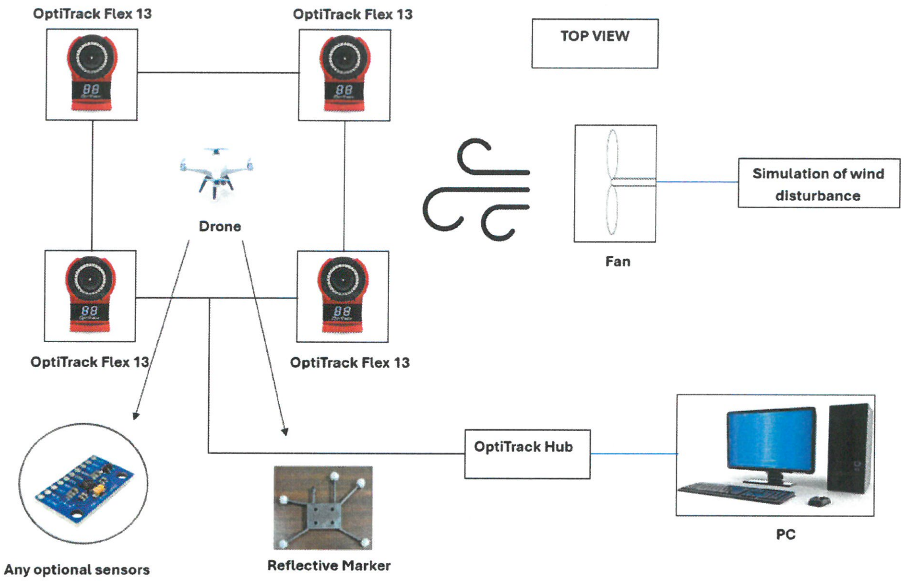

Figure 1. Full Layout Experiment Setup

It is recommended that two individuals be involved in the experimental procedures: one operating the PC for data logging and the other controlling the UAV. Maintaining a minimum distance of 2 meters between the cameras is advised, and ear protection is suggested. Before recording the flight data, it is important to rehearse the setup to prevent unexpected UAV movements, ensuring safety and effective communication between the two individuals.

Calibration of the cameras is crucial for mobile test rigs. The motion capture camera position and angle will be adjusted to record the drone's movement precisely and optimise the camera system. Experimental procedures are conducted, and real-time flight data consisting of position and orientation will be recorded using Motive software. The Optitrack Motion Capture System is utilised to replace the functionality of the Global Positioning System (GPS) for indoor operation.

All the data is then visualised using tools like Microsoft Excel and MATLAB for further analysis. The project aims to provide good recording measurements to gain valuable insights into VTOL UAV behaviour for intelligent fault detection and identification systems.

2.1 Setup for motion capture system

To record the real-time UAV flight data, a minimum of four OptiTrack cameras, as shown in Figure 2, should be securely mounted on a stable stand. It is crucial to ensure that the cameras do not vibrate during the flight test to maintain accurate data. However, it is worth noting that the OptiTrack system is vulnerable to infrared and sunlight reflection, which can affect the precision of the positioning and orientation streaming data and lead to ghosting marker recording.

Figure 2. OptiTrack Flex 13 camera

The OptiTrack Motive software offers a masking feature that removes unwanted reflections or unnecessary markers from the captured volume before calibration. The reflections can be seen in Motive Tracker software, as shown in Figure 3. However, it should be noted that the masking feature may lead to data loss in the masked areas when computing the 3D data, and excessive masking could result in frequent marker occlusions. To mitigate these issues, a black curtain, as shown in Figure 4, will cover the infrared (IR) reflections caused by any light.

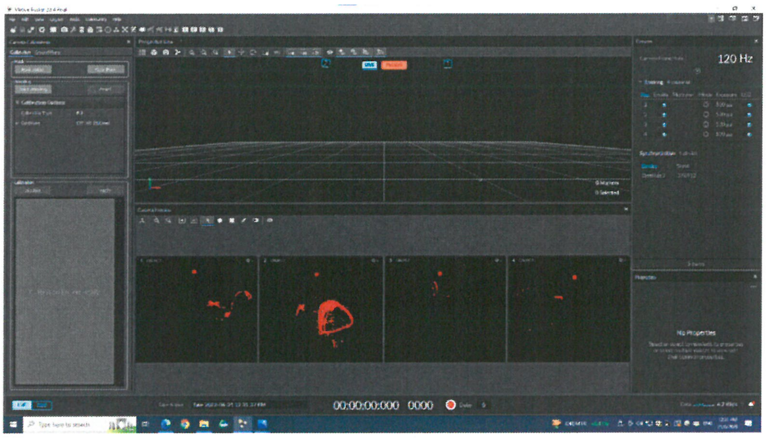

Figure 3. IR Reflection captured as red colour from the cameras

Figure 4. Black curtain to cover the reflection

2.2 Camera Calibration

Frequent camera calibration is crucial for mobile indoor test rigs due to its mobility functions. Figure 5 shows the calibration process for accurate and precise motion capture data. During calibration, the OptiTrack motion capture camera system will track and record the wand's movement using infrared markers. Several procedures are conducted to calibrate the camera system. First, the cameras on a stable tripod must be positioned and placed in the proper configuration to optimise capture area coverage. Then, the calibrated volume will be constructed within the capture region using the calibration wand. Calibration volume is a 3D environment established for tracking the reflective markers. The procedure enables the system to create spatial links between the cameras and the markers, allowing for reliable monitoring of marker positions in 3D space. The Motive Tracker software subsequently analyses the calibration data, determining camera locations and orientations relative to marker placements. During the motion capture process, this information is utilised to monitor and record the motions of the markers correctly. It is critical that the calibration volume spans the whole region of interest and is free of any impediments that might interfere with marker tracking.

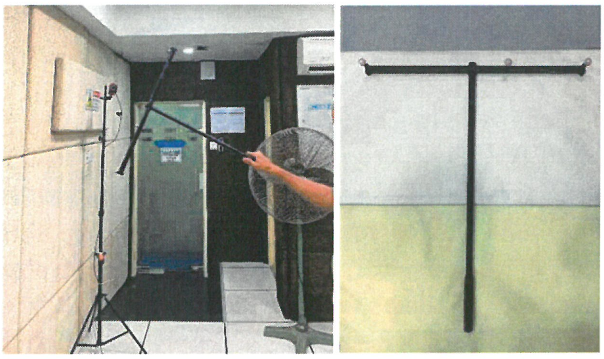

Figure 5. Calibration process(left) and calibration wand attached with reflective markers(right)

2.3 Set the Ground Plane

After the calibration procedure was completed, we needed to set the ground plane using a calibration square to enhance the accuracy of the motion capture system. The ground plane calibration square, as shown in Figure 6, is used to create a reference plane in the calibrated 3D environment. This square is a flat, triangle-shaped item placed on the ground or a flat surface within the capture area. The known size and location of the square are utilised to calibrate the device and match the collected data with real-world coordinates. Using the ground plane calibration square improves the accuracy and dependability of the motion capture system. It aids in the reduction of potential mistakes or disparities in collected data, particularly in applications requiring accurate location information, such as indoor VTOL UAV monitoring.

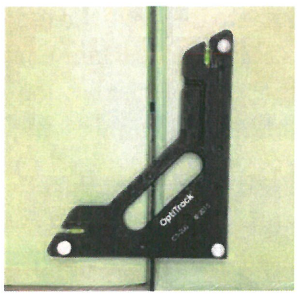

Figure 6. Calibration square used to set the Ground Plane

2.4 Reflective Marker for UAV Positioning and Orientation Tracking.

Asymmetrical positioning markers are attached to the UAV for position and orientation tracking. Utilising at least five markers, as shown in Figure 7, can improve recording precision in this experimental setup.

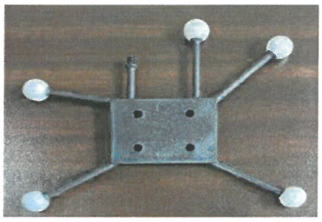

Figure 7. Reflective markers will be attached on top of the quadrotor UAV

2.5 Quadrotor UAV used in Experimental Setup.

Figure 8 shows the selected DJI Mavic Pro quadcopter used for this experimental setup, which comes with a flight controller. The DJI Mavic Pro is selected due to its renowned stability and versatility, making it a reliable choice for various applications. With powerful motors and advanced flight controllers, the DJI Mavic Pro ensures precise control and stability during flight. Its lightweight and compact design allows for easy transportation and enables both outdoor and indoor operations. Moreover, the quadcopter offers an impressive flight time, facilitating extended periods of uninterrupted flight and data collection.

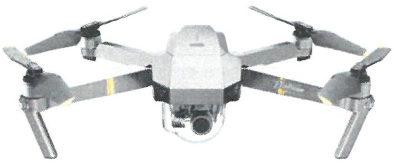

Figure 8. DJI Mavic Pro

2.6 Motive Tracker Software

Motive Tracker software is a crucial component in motion capture and tracking. It is OptiTrack's proprietary software designed exclusively for motion capture devices, such as the OptiTrack Flex 13 camera system. Motive Tracker has an easy-to-use interface that allows users to configure and manage the camera system, collect motion data, and conduct numerous analytic operations. It includes several features and functions to improve the motion capture process and extract useful information from the acquired data. Motive Tracker enables data export in various formats, including the Comma-Separated Values (CSV) format, for easy data handling and transfer into third-party applications or tools for additional analysis and visualisation.

2.7 Features Extractions and Machine Learning in Matlab

MATLAB is crucial in developing an intelligent VTOL UAV fault detection and identification system. It is a versatile software widely used in research and engineering. MATLAB enables data processing and visualisation, vital for extracting informative features from flight movement data. Information about the VTOL UAV's flight, such as position, orientation, and velocities from motion tracking cameras, will be beneficial in detecting and identifying faulty UAV flight features for intelligent VTOL UAV fault detection and identification systems.

3. Results

3.1 Mobile Indoor Flight Test Rig

Figure 9 depicts the front and top views for the whole architecture of the mobile indoor flight test rig. The stand fan is used during the flight test to simulate potential environmental disruptions by introducing airflow. Its location and distance from the quadrotor are carefully evaluated to achieve a regulated and stable flight environment.

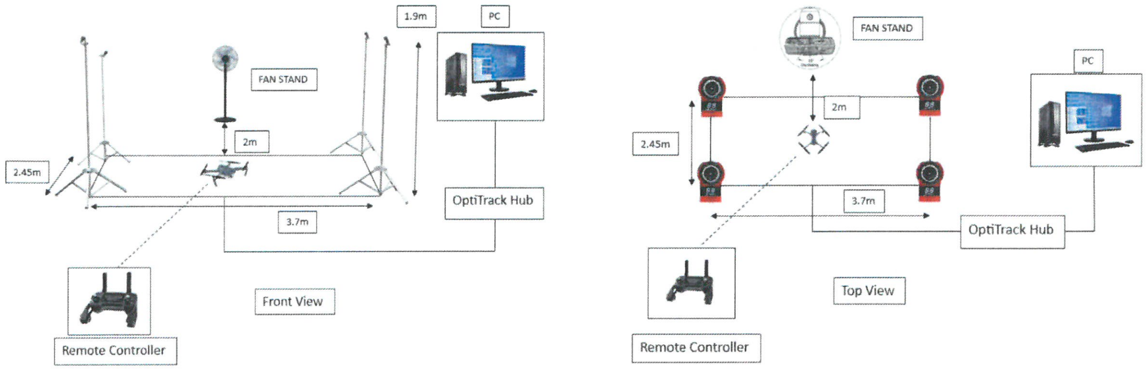

Figure 9. Front View and Top View of mobile indoor flight test rig

The four motion capture system cameras are deliberately positioned to precisely capture the quadrotor's movements and location. The cameras' location ensures excellent coverage and sight of the markers throughout the flying test. Proper wiring connections permit data transfer between the cameras, ground station control, and other attached devices.

The careful construction and setup of the experimental environment, as well as the calibration and positioning of the motion capture device, guarantee that the quadrotor's flight is correctly observed and tracked. This enables the collection of high-quality data, which can then be examined and assessed to evaluate the quadrotor's performance and optimise its design and control algorithms.

3.2 Test Area Preparation

The test area preparation is a crucial step for mobile UAV flight test rig. Figure 10 shows a regulated and constrained region for performing flight testing with dimensions of 3.7m x 2.45m. It comprises the hardware required to support the quadrotor UAV and motion capture system, such as a safe platform for take-off and landing and safety precautions to avoid mishaps. High-resolution cameras are carefully positioned as part of the OptiTrack Flex 13 system to offer the best possible tracking and data gathering. With this setup, it is possible to get valuable data on the UAV quadrotor's flight, including position and orientation. The test area will control and limits potential disturbance from the outdoor environment and provide accurate and trustworthy data collecting processes.

Figure 10. Mobile Flight Test Rig Setup

3.3 Calibration Test and Ground Plane

Calibration process will be visualised on Motive Tracker software as shown in Figure 11. This step is crucial to gain highly effective recording and eventually achieving precise tracking of markers. Factors such as light disturbances and masking were carefully considered during the calibration process. The calibration took place in a controlled environment with usage of black curtain to eliminate reflections and glare. Strategic placement of the cameras ensured accurate tracking from various angles, enhancing the calibration quality. Clear visibility of markers from calibration wand was crucial to minimize unobstructed line of sight between cameras and markers, enabling accurate tracking. The calibration area was expanded to cover the entire region of interest, ensuring comprehensive tracking of marker movements.

Figure 11. Calibration results in Motive Tracker software

Calibration square as shown in Figure 6 is used to set the ground plane in the middle of test area. Figure 12 shows the location of the calibration square as the origin for the recording area. The system improved its capacity to track the UAV correctly by matching the collected data with the known locations of the origin. This increased precision enabled a detailed examination of the UAV's flying position and orientation.

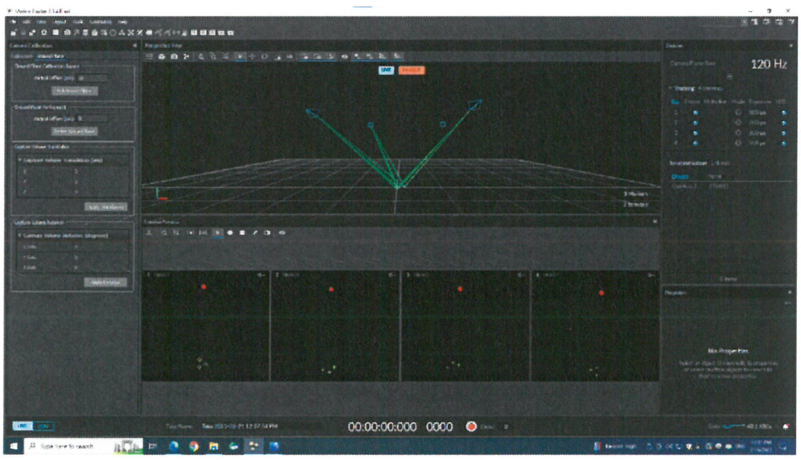

Figure 12. Ground Plane position captured as the origin for motion tracking volume.

3.4 Data Recording & Visualisation

The recorded flight data is loaded into Matlab from the Motive software in CSV format. This data will be used to build a visualisation in Matlab that illustrates the quadrotor's location within the test rig. We can visually observe the quadrotor's displacement and examine its movement and trajectory during the test by plotting this data in Matlab. The imported data include information such as time and the displacement of the quadrotor along the x, y, and z axes as shown in Figure 13.

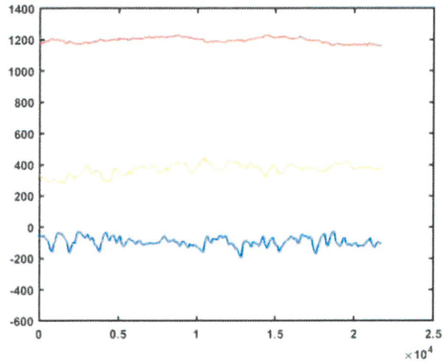

Figure 13. Displacement data along the x-axis (yellow line), y-axis (blue line), and z-axis (red line).

The MATLAB graph in Figure 14 shows the differences in quadrotor's stability when wind is applied during hovering in the test rig. The graph shows that the quadrotor keeps its location steadily for all axes without wind disturbance (refer left figure) and significantly deviate from the initial position with wind disturbance (refer right figure).

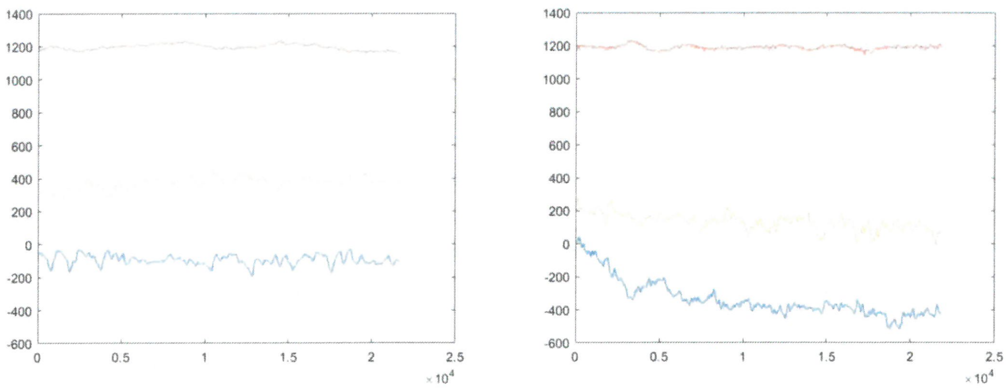

Figure 14. Displacement data for flight hovering with(left) and without(right) wind disturbance.

The graph in Figure 14 shows that the test rig can capture quadrotor's location for further data processing and informative features extractions using appropriate data driven analysis such as signal processing and statistical techniques. Boxplot graph in Figure 15 shows significant differences in data distribution between the two experimental conditions. Statistical comparison shows promising results for further UAV flight monitoring using the proposed mobile flight test rig using optical motion detection. Hidden features could be extracted to train and optimize machine learning classification algorithm. Application of machine learning in the diagnosis and prediction of UAV flight flying condition could reduce operational failure and major component faults in various flying environments.

Utilising OptiTrack motion detection cameras has the benefit of positioning flexibility in a desired indoor area for customizable quadrotor UAV performance monitoring and testing. They may be set up according to various experimental needs subject to regular camera system calibration for better precision and data reliability.

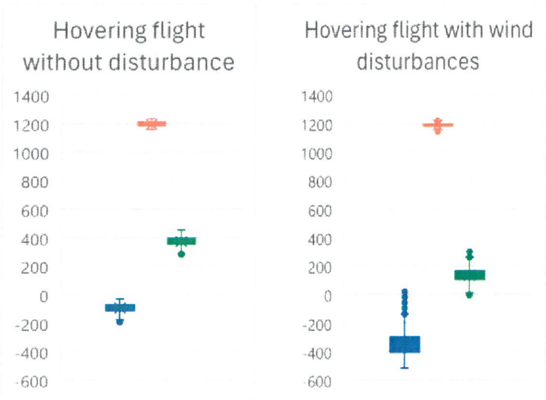

Figure 15. Boxplot graph shows significant differences in data distribution between the two experimental conditions.

5. Conclusion

There are several considerations for setting up an indoor flight test rig. First of all, the area must provide enough room for the quadrotor to conduct a variety of movements without any difficulty. This guarantees that the flight testing can be carried out efficiently and safely. It is essential to have sufficient space in all directions so that the quadrotor may move without the threat of running into humans, objects, or other machinery.

Additionally, the ground surface needs to be solid and appropriate for the take-off and landing of the quadrotor. The likelihood of disruptions or unforeseen movements during flight is reduced on a level, flat terrain. Removing any possible risks, such as loose debris or uneven ground, is crucial to provide a safe and stable operating environment.

Identifying significant design concerns and best practices was made possible by the detailed analysis of current indoor flight test rigs. This information formed the basis for creating a specialised test rig that satisfies the particular needs of VTOL UAV monitoring. The indoor flight test setup successfully made it easier to track and assess VTOL UAV performance. It offered a regulated setting for indoor flight testing, enabling accurate data gathering and analysis. The rig successfully recorded hovering flight data in a controlled non-windy environment and hovering flight data with wind disturbance. Statistical parameters prove its usefulness in capturing hidden informative features for different flight conditions using the proposed test rig.

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