Optical sensing of microsystem motion and performance

Scott C. Holswade* and Fred M. Dickey

Sandia National Laboratories, Albuquerque, NM 87185-0481

ABSTRACT

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Microsystems involve several fabrication technologies, but share the common trait of dimensions and motions measured in microns. Small feature sizes and deflections make the detection of microdevice motion particularly difficult. The rapid operating frequencies of many microactuators compound the detection problem. Effective feedback, control, and performance measurement of microactuators thus become problematic. These measurements are particularly important, however, due to the developmental nature of many microsystem technologies. Wear, lifetime issues, and optimized drive signals, for example, are poorly understood for many actuation devices. As microactuators move out of the development stage and begin to perform work on external assemblies and environments, the various load conditions will also come into account. Since microactuators involve small masses and inertias, effective driving of external loads may require feedback-based control of the microdevice. Optical sensing technologies offer solutions to these problems of sensor motion, microactuator analysis during the development process, and integrated feedback for microactuators driving external loads. Optical methods also lend themselves to the effectively one-dimensional nature of many microsystem motions, limiting the required signal analysis to practical levels that support real-time measurement and control. This paper describes several optical techniques for sensing motion, performance, and feedback data, some of which can be integrated with the microsystems themselves. For microactuators, experimental results indicate that real-time performance measurements are particularly revealing for understanding device motion and response. For microsensors, experimental results are also presented for interpreting motion using external and integrated optical techniques.

Keywords: Micromachines, actuators, optical probe, feedback, performance analysis

1. INTRODUCTION

Microsystems sensors and actuators often present a measurement challenge. Device dimensions are on the order of microns to hundreds of microns, and sense mechanisms move from fractions of microns to hundreds of microns, depending on the application. Electrostatic (capacitive) sensing has been proposed for measuring microsystem motion. For surface micromachines, it offers the ability to integrate directly on the same chip as the device. Generally, this approach has encountered significant problems due to the inherent small size of the signals obtainable at the scale of silicon microsystems. Sources of the problems include parasitic capacitance, grounding and shielding, charge build-up due to mechanical motion in the micromachine, and circuit loading (impedance) effects. Many of these concerns have been addressed in commercially available integrated accelerometers.^{1,2} For certain classes of sensors and for most actuators, however, capacitive sensing techniques have still exhibited problems.

Microsystem actuators often require performance measurement, especially during their developmental stages. Consider, for example, a surface-micromachined microengine, as shown in Fig. 1. This device consists of linear electrostatic actuators that are mechanically coupled to an output gear. Electrostatically applied forces are transmitted to the gear through mechanical linkages in a way that results in continuous rotation of the output gear.³ The output gear can be used to apply torque to a load device. The technology used to fabricate this microengine has been previously reported.^{3,4} In order to infer fundamental microengine device properties, such as spring constants, electrostatic force constants, and damping coefficients, measurements of the engine response to various applied drive voltages must be made.^{4,5,6} Time-dependent position measurements of the output gear are also required to measure frictional forces between the gear and hub, and to make performance tradeoffs of the engine in different applications.^{7,8} With the device properties quantified, microengine models can be developed and corresponding drive signals generated, at least for an isolated microengine. However, these models of engine behavior are frequently not sufficient for predicting performance, especially near structural resonant frequencies.^{9,10} Finally, real-time position measurements are anticipated to be instrumental in identifying fundamental degradation and failure mechanisms associated with the microengine.^{11,12,13}

* Correspondence: Email: scholsw@sandia.gov; Telephone: 505/844-8560, Fax: 505/844-8745

Fig. 1. Microengine diagram.

Optical techniques offer the potential for real-time position detection at a scale compatible with microsystem sensors and actuators. Optical methods have been used for some time to measure the performance of various microactuators. Gabriel *et al.* developed a laser-based probe for measuring real-time deceleration of unpowered turbines and gears.¹⁴ In their probe, a beam from a HeNe laser was focused onto the turbine or gear teeth and the scattered light was collected directly by a photodiode. The resulting signal allowed them to count teeth and thus measure turbine position versus time. For LIGA-fabricated micromotors, Guckel *et al.*¹⁵ and Sun *et al.*^{16,17} used integrated optical shaft encoders to record device motion. These encoders utilized photodiodes positioned below the device rotor and illuminated from above. Ruther *et al.* measured the bending of cantilevered beams with an integrated displacement sensor consisting of three fibers and a movable mirror in an optical bridge configuration.¹⁸ Burdess *et al.* used a laser vibrometer to measure vibrational modes of micromachined beams and bridges.¹⁹ Dickey *et al.* developed an optical probe to measure rotational performance of microengines.²⁰ These optical probes can be tightly integrated with both LIGA-based and surface fabrication-based microengines.^{21,22} This technology has been previously reported in detail,²³ and it will be briefly reviewed in the next section. The optical probe approach is analogous to techniques used in optical shaft encoders²⁴ and optical disk technology.²⁵ Linear micro encoders, consisting of two sources and detectors positioned in quadrature phase with respect to a pattern have also been constructed.²⁶

2. MICROMACHING OPTICAL PROBE

Among the possibilities for optical probe geometries, forward scatter and backscatter offer distinct advantages. They are fairly easy to implement, and they provide relatively strong detected signals. By keeping the area immediately above the MEMS device clear, they allow simultaneous visual inspection. Finally, the phase relationship between the two signals can be used to determine gear direction. The Micromachine Optical Probe is thus based on the simultaneous measurement of forward and backscatter. A schematic of the probe is shown in Fig. 2(a). The source is a 1 mW HeNe laser, which is coupled to a 5 μm core single-mode fiber. Lens L_1 collimates the fiber output and lens L_2 is chosen to give a nominal 3 μm focused spot at the working surface. The backward scattered light collected by L_2 is directed to lens L_3 by the beam splitter and focused on a 1 mm multimode collecting fiber. The forward-scattered light is collected by a 1 mm multimode fiber. The axes of the incident (backscatter) and forward scatter beams are coplanar and directed at an angle of 45 degrees with respect to the surface normal. This configuration of optical signals and detectors is effectively one-dimensional, and it offers the potential of bandwidths in the GHz range. This is sufficient for gears that can be driven at 5 kHz. A possible refinement of the probe for future work would be to bring the source beam in at or near to normal incidence to the micromachine substrate. A split detector would then be used to interrogate the scattered field to determine the direction of rotation.

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Fig. 2. (a) Schematic diagram of optical probe for forward and backscatter signal detection. (b) Forward and backscatter geometry.

Fig. 2(b) shows a side view of a gear and substrate that are illuminated by the optical probe. Two specular reflections are formed when the outside sections of the incident beam reflect from the substrate and the gear. The side surfaces of the gear tooth and the substrate form a roof reflector that creates two backscatter reflections from the substrate-to-gear and gear-to-substrate paths of the incident light. While this figure shows the conceptual idea of the forward and backscatter beams, the best signals were obtained with more complicated reflection geometry. The best backscatter signals were experimentally observed when the probe beam was incident on the gear at 45° to the tangent. In this case, the incident beam scattered from a corner reflector formed by the substrate, the gear tooth wall, and the inner diameter of the gear.²³

3. SURFACE MICROMACHINED ACTUATORS

Surface micromachine actuators are being extensively studied for operational reliability. Stiction and wear have been identified as primary failure mechanisms.²⁷ For both of these mechanisms, device design and material choices can reduce their effect on actuator reliability. At the same time, however, proper operation of the actuator reduces both wear effects and the possibility of stiction and failure. The microengine illustrated in Fig. 1 is a physically constrained system. The gear hub constrains the motion of the rotating gear, and linkages connected to this gear constrain the motion of the comb drives. The system's dynamical behavior results from the balance of all the forces acting upon it. The system is ultimately controlled by the electrical drive signals applied to the comb drives. Properly selected drive signals will minimize constraint forces required to balance effects such as inertia. These constraint forces, when acting upon rubbing surfaces, will lead to premature failure in the microengine.²⁸ As an example, it is desirable to operate the microengine of Fig. 1 in a way that eliminates radial forces on the gear pin joint. These radial forces cause the gear to rub against its hub. Excessive radial and tangential forces also lead to early failure in the pin joint itself.²⁹

Extensive modeling has occurred to derive optimized drive signals for the microengine.^{7,8,10,30} Experimentally measured microengine parameters provide the constants for an equation that produces the engine drive voltages. These model-based drive signals have been shown to greatly extend microengine lifetimes. However, these drive signals may still not be optimum for several reasons: (a) there are terms that were ignored in deriving the equation; (b) variations in fabrication may cause the constants for a particular engine to vary from the values used in the drive signals; and (c) the values of the constants will change as the engine wears. As an example, consider the behavior of the microengine shown in Fig. 3. This graph shows the amplitude of the backscatter signal as a function of time. Two revolutions of the gear are shown, so peaks corresponding to 38 teeth appear for each measurement. The uneven spacing of the peaks implies non-uniform rotation of the gear. In fact, there are known issues with this generation of microengines that are causing at least some of the non-uniform behavior.^{7,8} Nonuniformity of other microactuator technologies has also been observed.³¹ Finally, notice the difference between the signal obtained early in the engine's life and that obtained 50 minutes (roughly 3×10^5 rotations) later. Besides a shift in the position of some peaks, there is a less uniform spacing. The microengine is thus not responding to the drive signals in quite the same way, and it is running less smoothly. This difference is due to some change in the microengine properties, most likely due to wear. The graphs of Fig. 4 illustrate non-repeatability in the gear motion. Fig. 4(a) shows five consecutive rotations during early engine life. Notice that this engine runs fairly consistently. However, Fig. 4(b) shows that the microengine is experiencing non-periodic behavior after 50 minutes. In summary, a degradation mechanism, most like wear, is causing the microengine to experience additional constraint forces as it ages.

Fig. 3. Backscatter signal returned by probe for two consecutive revolutions of the gear. Gear running at 100 Hz. Initial motion was soon after the gear was started. Final motion was 50 minutes later.

Fig. 4. Superimposed backscatter signals for 5 consecutive rotations of the gear. (a) Initial behavior of engine. (b) 50 minutes later.

For many microengine designs, drive signals are currently optimized in the laboratory by manually adjusting the parameter constants in the drive signal equations.³² This tuning is currently accomplished by observing the uniformity of rotation using strobe microscopy.³³ It accounts for initial deviations from the model or the parameters for a particular gear. This technique is time consuming and does not address parameter changes, such as those introduced by wear, as the engine ages. At the same time, microengines that are performing useful work experience load effects that will further change the dynamical behavior of the system. The equations describing the isolated system are currently fairly complicated, and it is likely that changing load conditions will lead to dynamic behavior that can no longer be completely modeled. Drive signal optimization based on real-time actuator feedback, such as that provided by the micromachine optical probe, should be able to reduce engine constraint forces to the lowest possible levels and adjust for wear effects and changing load conditions. This would run the engine at its maximum power output with the longest operating life.

4. INTEGRATED LIGA READOUT SYSTEM

This optical probe technology can also be applied to microsystems based on LIGA^{34,35} fabrication technology. Similarly to surface micromachined devices, integration of LIGA micro-fabricated actuators into a complete microelectromechanical system requires an understanding of their dynamic behavior and may entail position feedback control. An example device is the LIGA "milliengine", which can serve as a generic actuator for LIGA based microsystems.³⁶ Fig. 5 shows a micrograph of the pinion gear, output gear, and drive link connection for this engine.

Fig. 5. Illustration of the pinion gear assembly for a LIGA milliengine.

The micromachine optical probe in a forward/backscatter-based system has been used to analyze the behavior of these actuators in a manner similar to that for surface micromachined devices.²¹ However, the optical probe can scale with the larger size of the LIGA devices and should therefore offer easier implementation. An example of an integrated implementation is shown in Fig. 6(a). In this approach, a central waveguide illuminates structures on the sidewalls of the LIGA device and receiver waveguides capture the signals scattered back. By properly spacing the waveguides, gear direction can be obtained. Fig. 6(b) shows an implementation of this approach using optical fibers. The backscattered radiation coupling into the lower fiber is visible.

Fig. 6. (a) LIGA probe concept using waveguides. (b) Micrograph showing scatter of beam from central waveguide to bottom waveguide.

These fibers were bonded together for ease of handling. This particular gear was isolated on a hub and rotated in both directions using a jet of air. Fig. 7 shows oscilloscope traces of the signals returning from the two receiver fibers. Notice that the phase relationship between upper and lower fibers reverses with the reversal in gear direction. The phase delay is very close to 90° between peaks, which maximizes the ease in automatically interpreting the signals. Rotation of the fiber bundle around the central fiber axis can reduce the apparent distance between them and thus adjust the phase delay between fibers. For finer resolution of gear angular position, several such assemblies could be mounted around the gear in a vernier arrangement.

Fig. 7. Scope traces showing gear rotation. (a) Gear moving CW. (b) Gear moving CCW.

5. MICROMACHINE ACCELEROMETER AND READOUT

While capacitive accelerometers are now commercially available,^{1,2} there are other accelerometer applications that would benefit from unambiguous signal generation. This is often implemented as a pattern output, with a correct pattern occurring in the correct acceleration environment. Surface micromachine and LIGA-based accelerometers are being designed for these purposes. One implementation, shown in Fig. 8, consists of a sense-mass suspended on springs that moves in response to linear acceleration. Embedded in the sense-mass are a series of slotted holes that represent four channels of information, two clock channels, one data channel and a reference channel. An optical readout scheme reads the four channels as the sense-mass translates past. The device uses the clock channel measurements and quadrature logic to read the data channel. This logic requires a data bit to be measured every time a clock channel changes state.

One optical readout implementation uses waveguide-based optics, which are implemented as a photonic integrated circuit (PIC). The PIC is flip-chip bonded over the micromachine, for a compact package, as shown in Fig. 9. The shuttle moves 500 μm during readout, and each code element is 17 μm wide. As shown in Fig. 9, the PIC contains an integrated laser that is incident upon a mirror at 22.5°. The mirror reflects the radiation at 45°, where it travels down to the accelerometer shuttle. The particular readout scheme makes use of backscattered radiation from etched features in the accelerometer shuttle. The shuttle is etched to create corner reflectors that return radiation back toward the source for a "one" bit. The signal reflects from the shuttle wall and the substrate below the shuttle. For a "zero" bit, the shuttle is not etched, and the radiation scatters from the top of the shuttle in the forward direction, away from the detector. This arrangement provides a large signal difference between a "one" and "zero" signal, since the "zero" signal returns virtually no signal to the detector. It is thus superior to schemes that interrogate the code vertically, which have a limited contrast between a "one" and a "zero." The shuttle is gold-coated to improve reflectivity and thus the amplitude of the "one" signals.

Fig. 8. (a) Surface micromachine-based accelerometer. (b) LIGA-based version.

Fig. 9. Optical readout scheme. (a) The PIC is mounted above the moving shuttle. (b) Side view.

The PIC for this readout is currently in fabrication. Fig. 10 shows enabling technologies for the device. In Fig. 10(a), a waveguide splitter directs radiation to four channels, where it is directed at 45° to the waveguide plane by integrated mirrors. Fig. 10(b) shows an enlarged view of the integrated mirror designed to reflect the radiation at 45° to the waveguide plane. The final mirror contains a concave shape that focuses the beam at the shuttle in the axis of the shuttle motion. This allowed the code width to reduce to $17\text{ }\mu\text{m}$ per bit and thus reduce the total shuttle movement.

Fig. 10. Enabling technologies for photonic integrated circuit (PIC) readout.
(a) Waveguides producing out-of-plane source signals. (b) Close-up of mirror.

To test the backscatter/forward scatter readout scheme, a mock shuttle code was constructed by etching features into a silicon substrate. These features were gold-coated, just as in the actual shuttle. To simulate the shuttle moving under a fixed PIC as it would in an acceleration environment, a commercially available waveguide source was scanned over the mock code, as shown in Fig. 11(a). The single mode waveguide was connected to a HeNe laser source. A multimode fiber mounted below the waveguide collected the backscattered radiation. This arrangement was not ideal, because the backscattered light tended to return to the source waveguide rather than the collection fiber. The waveguide thus had to be backed away further from the code than desired, in order to capture sufficient return signal. The spot on the code was thus larger than would occur with the PIC device. Nevertheless, the simulated arrangement provided a usable signal, as shown in Fig. 11(b). The figure shows the detected signal from the 24-bit code sequence, as the waveguide was scanned over the mock code. The figure also shows the signal from an ideal readout mechanism (dashed line) for comparison. The signals from "zero" bits that were surrounded by "one" bits did not completely return to zero. This is a consequence of the optical spot being larger than desired, and thus reading information on the boundaries of the desired code element. The effect is greatest for isolated "zero" bits.

Fig. 11. (a) Simulated readout system. (b) Detected signal as waveguide was scanned over mock pattern.

6. OPTICAL DETECTION OF FINE MOTION IN LIGA DEVICES

In many cases, such as the LIGA-based accelerometer of Fig. 8, it is advantageous to minimize the size of the optical beam on the target area to allow measurement of fine motion. LIGA technology offers a convenient way to both focus radiation from a source waveguide and align the optical system to tight tolerances. Fig. 12 shows a LIGA-fabricated structure in PMMA material that generates a narrow optical beam at the target area as well as providing mounting fixtures for source and receiver fibers. In the view of Fig. 12(a), a single-mode fiber supplying 635 nm radiation is held in place by the horizontal channel. The fiber rests at stops that hold a proper object distance for the focusing lens. The aspheric lens demagnifies the beam and focuses it at the target spot. A 100 μm core receiver fiber is held in place by the vertical channel. The lens and channels are all part of a monolithic structure. The PMMA structure is mounted using a combination of interference-fit precision pins (scallop holes) that provide alignment to a matching substrate and other pins in slightly oversized holes that provide extra strength. Two breakaway beams are used to hold the structure together until the pins are in place. The fibers are then dropped into their respective slots and slid forward until coming to rest on the stops. These LIGA structures could also be used directly with sources and detectors, rather than fibers. The structure would be designed to hold the laser and detector die in precision alignment with the lens and target assemblies.

Fig. 12. LIGA-based optical readout structure. (a) CAD layout drawing. (b) SEM of PMMA structure (500 μm thick).

One of the advantages of LIGA technology is the ability to fabricate cylindrical lenses of arbitrary shape. This lens was a multi-order aspheric optimized for minimum spot size at the target plane. The biconvex design for this lens was chosen so that the curvature of each surface was minimized, in an attempt to minimize the effect of fabrication errors. The source fiber has a numerical aperture of 0.16, while the object numerical aperture of the lens is 0.24. It is thus capturing about 99% of the

emitted optical power from the source fiber. This lens produces a line focus at the target plane, which interrogates features on the sides of LIGA sensors, as shown in Fig. 13(a). A cross section of the calculated target focus is shown in Fig. 13(b). The optical design was imported into the CAD program used for LIGA mask layout, and then the rest of the structure designed around it. The mask was fabricated using a $0.25\text{ }\mu\text{m}$ step size. Finer mask steps are also available. Fig. 14(a) shows an SEM micrograph of the lens sidewall from the source fiber vantage point. The vertical structure is the result of mask resolution limits. Some horizontal striations also appear, which are the results of fabrication nonuniformities.

Fig. 13. (a) Optical readout structure interrogating a sensor. (b) Cross-section of target line focus. The width is roughly $1\text{ }\mu\text{m}$.

Fig. 14. (a) SEM photograph showing view of lens sidewalls. Vertical structure from the mask steps is visible, as well as some small striations in the horizontal directions. (b) Microphotograph of the structure.

The LIGA-based lens was evaluated for target spot width using a knife-edge scanning technique. A detector was placed on the optical axis past the focal region, and a razor blade was translated through the focal region, as shown in Fig. 14(b). The razor blade was focused by positioning it for minimum observed beam width. Fig. 15 shows the differentiated transmitted power signal from the lens. The FWHM value of the peak is $2.3\text{ }\mu\text{m}$. Some fraction of this observed width is likely due to nonuniformities in the edge of the razor blade. If this value is corrected for normal incidence (the knife edge scan was 45° to the beam axis), it becomes roughly $1.6\text{ }\mu\text{m}$. This compares favorably to the predicted beam width of $1\text{ }\mu\text{m}$ from Fig. 13(b), and it indicates that the LIGA-based fabrication method delivers acceptable optical quality.

The system architecture was also experimentally evaluated to determine the minimum feature size that it could resolve, including effects of the receiver geometry. This was done by translating an aluminized bar target on a transparent substrate, and observing the signals returned from the receiver fiber. The bars and spaces were $100\text{ }\mu\text{m}$ wide. The target was focused by positioning it for minimum measured rise distance (where the beam went from a transparent part to a reflective part). Fig. 16(a) shows the return signal for a 1 mm translation of the bar target past the measurement point. The structure observed at the high signal levels is mainly due to reflectivity changes in the aluminum bars. Also, the edges of the bars generally

Fig. 15. Differentiated transmitted power as knife edge translates through beam.

Fig. 16. (a) Receiver fiber signal from bar target. (b) Expanded time scale for one edge (3 passes). The signal rise occurs in roughly $2\text{ }\mu\text{m}$.

exhibited a transition zone rather than a step behavior. By finding a very sharp reflection transition on one of the edges, a good measurement of the target beam width could be found. Fig. 16(b) shows this behavior for three different passes in an expanded scale. Again, the structure at occurring after the signal rise is most like due to reflectivity differences in the aluminized bars. Note that this same structure appears for each pass of the beam. The rise distance between the 10% and 90% levels is less than $2\text{ }\mu\text{m}$. Thus, we should expect this readout scheme to successfully interrogate sensor features as small as $2\text{ }\mu\text{m}$ in width. If the beam width obtained from the rise value is corrected for normal incidence (the scan was 45° to the beam axis), it becomes roughly $1.4\text{ }\mu\text{m}$. This compares favorably to the predicted beam width of $1\text{ }\mu\text{m}$ from Fig. 13(b), and it indicates that the LIGA-based fabrication method delivers acceptable optical quality.

Another possibility for providing fine interrogation of microsensors is to precisely position lensed waveguides. The waveguides would focus the guided radiation, providing standoff from the moving component, a smaller beam on the target, and coupling of the return radiation back into the waveguide. This would allow a single waveguide to perform the source and pickup functions. An example of such a focusing waveguide is the lensed fiber. This structure can be made by grinding the fiber tip into a conical shape.³⁷ A LIGA-fabricated structure can then be used to precisely position the lensed fiber to interrogate a moving sensor, as shown in Fig. 17. The enlarged view of the target area shows spring guides that center the fiber into a stop angled to accept the conical fiber tip. These structures have been fabricated and are currently undergoing evaluation.

Fig. 17. LIGA structure designed to hold a lensed fiber in place for sensor interrogation.

7. FUTURE DIRECTIONS

Micromachine probe technology provides a great deal of information about actuators, but it does not directly provide velocity information. Velocity must be inferred for the time between features moving past the probe beam. Also, fine motion between these events is not captured. A potential upgrade to this system would be to utilize a laser vibrometer to provide the source beam and interpret the backscatter radiation.¹⁹ This would provide velocity information, at least for the times in which actuator features were returning a backscatter signal. It would also provide actuator direction and eliminate the need for interpreting the relative phase of forward and backscatter beams.

For microsystems, optical sensing reaches its highest utility when it can be integrated with the sensor or actuator. For LIGA-based sensors and actuators, schemes such as those described in sections 4 and 6 provide this integration. However, for surface micromachine devices, the micromachine optical probe must be refined from a bulk optical arrangement to an integrated structure. There are several possibilities for integrated probes, including waveguides on the same die as the surface micromachine, as shown in Fig. 18. These could be implemented in polymer materials,²³ or possibly in SiO_2 that is protected from the final micromachine release etch. This approach is identical to that used for LIGA structures as shown in Fig. 6. Another implementation involves a through-wafer architecture to interrogate the surface microdevice.³⁸

Fig. 18. Integrated optical feedback system for surface micromachine devices.

8. CONCLUSIONS

This paper discussed the advantages of optical technologies for recording the motion of microsystem sensors and actuators. For surface microengines, optical probe technology can successfully reveal performance and degradations due to wear mechanisms. It should also provide the feedback necessary to optimize the engine drive signals for peak power output and minimum wear, especially under changing load conditions. This technology has been applied to LIGA-based devices, and it

has been successfully integrated using waveguides. For certain classes of microsystems sensors, both LIGA and surface micromachine based, optical technology can successfully interrogate patterns on the devices that produce unambiguous evidence of the sense environment. Properly implemented, this technology is relatively immune to noise sources owing to its high signal contrast. These readout schemes can be further refined to interrogate fine motions, on the order of a couple of microns.

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