Flexible Optical Fiber Bending Transducer for Application in Glove-Based Sensors

Eric Fujiwara, Murilo Ferreira Marques dos Santos, and Carlos K. Suzuki

***Abstract*— The development of a low-cost and flexible optical fiber transducer for measurement of angular displacements is reported. The light intensity attenuation due to fiber microbending losses is correlated to the variations in flexing angle, yielding to a sensitivity of 1.80°. The device was also mounted in a fabric glove to the monitoring of flexion and abduction movements of index and thumb fingers. Once calibrated by a simple procedure, the glove-based system was capable to measure the angular positions with average errors <5° and 7° for interphalangeal and metacarpophalangeal joints, respectively. Additionally, the repeatability analysis resulted in average range and standard deviations of 8.06° and 3.45°, respectively. The optical fiber sensor provides a low-cost alternative to the real-time monitoring of hand posture, and can be suitable for applications in human-robot and human-computer interactions**

***Index Terms*— Data gloves, motion measurement, optical fiber sensors, wearable sensors.**

I. INTRODUCTION

THE real-time detection of hand movements is essential for manipulation tasks in advanced mechatronics systems. Applications of such kind of technology can be evidenced on the teleoperation of robots provided with dexterous end-effectors that can be utilized, for example, on space [1], [2] and underwater exploration activities [3], as well as on the fields of medicine and therapy, like robotic-assisted surgery [4] and rehabilitation [5]. Additional applications include human-computer interaction in virtual-reality environments [6] and gesture recognition for communication [7] and entertainment [8].

Even though a variety of techniques was proposed to the measurement of hand posture – such as optical tracking with external cameras [9], acoustic and magnetic tracking [10], and electromyography [11], – glove-based sensors present advantages in terms of real-time response and portability, and are unaffected by latency and fingers occlusion [12], [13]. However, the design of such instrumentation must take account of certain operational requirements, including accuracy, comfort to the user with low mechanical load or movement restrictions, fast calibration and relative low cost [14].

Most of the transducers applied on glove-based devices make use of electrical, magnetic or optical measurements to the estimation of finger joints displacements. Commercial systems, such as the CyberGlove (Cyber Glove Systems) and 5DT Data Glove (Fifth Dimension Technologies), are equipped with proprietary piezo-resistive and optical fiber transducers [12], respectively, and have been successfully implemented on teleoperation and medical applications [15]–[17]. Although such technologies are suitable for aforementioned applications, their relative high cost might be a limiting factor for a widespread use.

Experimental approaches also include resistive flexsensors [14], [18], conductive mixtures to be printed directly on fabric surface [19], and carbon nanotube strain sensors [21], in which the sensor resistance changes as a function of the exerted bending angle or strain. Alternatively, magnetic induction devices mounted close to finger joints can be used to detect the hand movements, based on the variation of induced electromotive force due to changes on relative position of transducers [20]. However, most of these approaches are susceptible to electromagnetic interferences, and can exhibit limitations in terms of response linearity.

On the other hand, optical fiber sensors present attractive characteristics for motion detection systems, like flexibility, lightweight, high sensitivity, multiplexing capability and immunity to electromagnetic interference [22], [23]. In this sense, recent researches demonstrated the implementation of fiber Bragg gratings [24], hetero-core fiber bending schemes [25], enhanced plastic fiber curvature sensors [26], and flexible fiber bending transducers [27], [28] on the monitoring of human hand or body movements.

Present paper reports the development of an optical fiber microbending transducer with a low-cost, flexible and compact design, for the measurement of angular displacements, using standard waveguides and a simple interrogation scheme. This approach avoids more complex setups, as the use of fiber gratings and tapered fibers, for example. The devices were mounted on a fabric glove and allow monitoring the flexion and abduction movements of index and thumb fingers joints. After performing an intuitive and relatively fast calibration procedure, the system was capable to estimate variations on user hand posture in real-time. Furthermore, the glove-based system was evaluated in terms of measurement error and repeatability.

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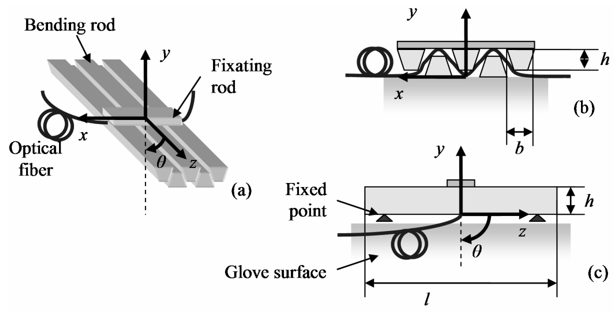

Fig. 1. (a) Optical fiber bending transducer: (b) frontal and (c) lateral views.

II. Sensor Design

A. Optical Fiber Transducer

The transducer comprises of N flexible silicone structures with length l, height h, and bases of dimensions b and $b/2$, positioned in a periodical fashion as presented in Fig. 1. The optical fiber is placed in the gap between bending rods, which forms a periodical deforming structure, and the transducer is installed above the dorsal side of monitored finger joint by attaching the edges of silicone structures to fabric glove surface using an adhesive gel, in order to keep the center of the transducer over the monitored joint.

As the user flexes his or her finger by angular displacement θ, the silicone rods are stretched causing the fiber to be pressed by the periodical structure. In this sense, light attenuation by microbending is induced due to the mechanical perturbations applied in the waveguide, in which the repetitive small-radius curvatures cause energy coupling between guided and radiation modes [29], and consequently the variations on light intensity can be correlated to the angular displacements of flexed joint. Furthermore, power losses are also induced by light absorption caused by the polymer buffer, reducing the recoupling of cladding modes to the core modes [30]. Eventual macrobending losses caused by additional fiber curvatures that are not related to the transducers were also avoided by placing the waveguides inside rigid tubes, providing additional mechanical protection.

In order to avoid lateral deformations of the bending structures during flexion event, which could reduce the device sensitivity, a thin silicone rod is glued to the transducer at the center of its external side by using the adhesive gel, making the distance between rods to be preserved even with the application of larger angular displacements. Moreover, the glove is tightly adjusted to the user hand for prevention of most of wrinkles and slides of fabric glove over the skin during the performing of movements, which also could affect the sensor sensitivity. Even thought the transducers cause a subtle restriction on maximum flexion of some fingers joints, mostly due to the mechanical characteristics of fiber and stress-applying components, the glove-based device was designed to properly fit to the user anatomy, allowing the execution of hand movements in a natural and comfortable way.

B. Experimental Setup

The experimental setup is illustrated in Fig. 2. The light emitted by a continuous white LED source is launched into the ~2 m length silica standard multimode fibers (plane-polished with polymer buffer coating) by using a mechanical stage. The sensing fibers are attached to the bending transducers according to the configuration presented in previous section, and the optical signals intensities are measured by a CCD with 15 Hz sampling rate. In addition, the source stability is also monitored by a reference fiber, which delivers the light emitted by the LED directly to the detector. The acquired data is then processed in a routine developed under MATLAB environment, which performs the cancellation of source fluctuations by dividing the intensities of sensing fibers by the reference, and subsequently the normalization of optical signals. Concerning the implementation of the glove-based sensor, a graphical user interface was programmed with MATLAB in order to provide functionalities for calibration routines, and further real-time reproduction of user hand posture by a virtual anthropomorphic manipulator given the angular positions calculated from acquired normalized intensity values.

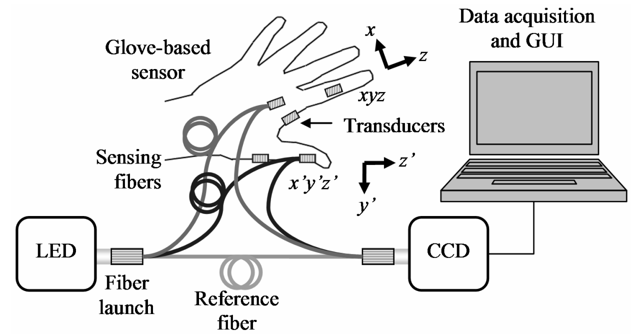

Fig. 2. Experimental setup for measurement of angular displacements. Coordinate system (x,y,z) is related to index PIP and MCP joints, whereas (x',y',z') regards to thumb IP and MP joints.

TABLE I
CONSTRUCTION PARAMETERS OF THE BENDING TRANSDUCERS

Transducer	N	b (mm)	Fiber configuration
T5F1	5	4	(i) Straight
T7F1	7	2	(i) Straight
T5F3	5	4	(ii) 3 loops
T5F6	5	4	(ii) 6 loops
T5FU	5	4	(iii) U-bending

C. Sensor Characterization

In order to evaluate the effect of transducers configuration on sensor response, a preliminary experiment was conducted by testing different designs for the device, according to the parameters summarized in Table I. The width b and number of bending rods N were varied from 2 setups, whereas the length $l = 25$ mm and height $h = 3$ mm were kept constant. Regarding the optical fiber installation into the transducers, 3 configurations were considered, as shown in Fig. 3: (i) the fiber is normally placed in a straight line; (ii) the waveguide is coiled in loops and passes several times by the periodical

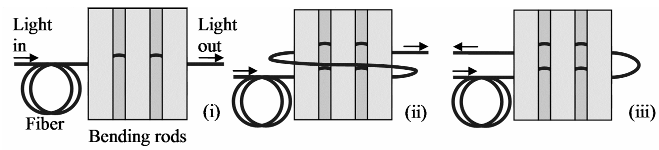

Fig. 3. Fiber configurations inside the bending transducer: (i) straight line, (ii) loop and (iii) U-bending.

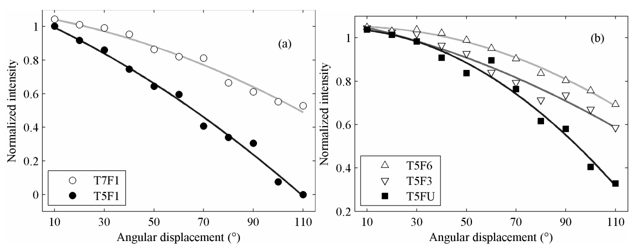

Fig. 4. Effect of transducer design on light attenuation: variation of (a) bending rods and (b) fiber configuration. Experimental data was fitted by second degree polynomial functions.

structure; (iii) the fiber is bent in U-shape (half loop) inside the transducer. The purpose of configurations (ii) and (iii) was to increase the length of fiber that was subjected to the microbending effect.

The transducers were mounted on a support comprised of two PVC plates spaced by 10 mm, and then flexed using a moving stage, according to predetermined angles ranging from 0 to 110°, by maintaining the nominal displacement $\Delta\theta$ constant during each measurement. The normalized intensity value corresponding to each position was obtained by calculating the mean of 600 data points, whereas the nominal angular displacements were set and measured with a protractor.

As noted in Fig. 4, all configurations exhibited a higher sensitivity for displacements from 40° to 110°, which demonstrates a good reliability on the measurement of larger angle values. In particular, the transducer T5F1 presented the best response for angular displacements $<40°$, making this setup more suitable for such kind of measurement. In this case, the sensitivity was $\sim$1.80° for $0° \leq \Delta\theta < 40°$, and $\sim$1.10° for displacements $\geq 40°$.

Concerning the configuration of bending structure, a higher sensitivity was obtained for $N = 5$, as shown in Fig. 4(a). Even though the case $N = 7$ was designed with more stress applying parts, which was supposed to increase the optical losses, this setup yielded to a less sensitive result probably because of the reduction on bending structure periodicity [30], determined by b. On the other hand, it is not convenient to increase N by maintaining $b = 4$ mm, since the transducer must be as compact as possible in order to fit to the user hand and not apply excessive mechanical load during the movements.

With respect to the fiber configuration, in contrast to the initial prediction, the increase of fiber length subject to bending structure did not result in a better response to angular displacements, making the straight arrangement (i) more suitable than the alternative approaches (ii) and (iii). This observation can be explained because both loop and U-bend geometries introduce macrobending losses in the fiber, which reduce microbending sensitivity due to removal of high order modes of the fiber core [30]. Such statement is confirmed by analyzing the curves for configurations (ii) and (iii) in Fig. 4(b), since the sensor response is significantly deteriorated with the increase of fiber curvatures.

It is worth noticing that all experiments were carried out under room temperature, which corresponds to the utilization of the glove-based device under normal conditions. However, it is expected that increasing the operation temperature would also induce variations on mechanical and dimensional characteristics of stress-applying parts, consequently modifying the periodicity of microbending transducer or changing the stain to which the fiber is subjected. This would result in variations on transducer response, demanding corrections for the temperature factor.

III. Measurement of Hand Movements

A. Hand Movements

The human hand can be modeled as a chain of successive joints and links resulting in a structure with $\sim$21 degrees of freedom (DOF). The index, middle, ring and little fingers are comprised of distal interphalangeal (DIP), proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joints, being the DIP and PIP characterized by flexion/extension movements (1 DOF), whereas the MCP joint can perform both flexion/extension and abduction/adduction motions (2 DOF). Moreover, the thumb kinematics are defined by its interphalangeal (IP), metacarpophalangeal (MP) and trapeziometacarpal (TP) joints, with 1 DOF for IP and MP flexion, and up to 3 DOF for TP movements [12], [31]. The hand representation can be also simplified due to natural constraints of human anatomy, such as the dependence of DIP angular position on PIP joint flexion, as well as the limitation on middle finger MCP abduction/adduction movement [31]. This approach is suitable to the optimization of glove-based sensor design, because for some applications, the hand posture can be estimated by monitoring a reduced number of DOF, which requires the installation of fewer transducers.

B. Calibration Curves

The transducers were mounted on the glove in order to investigate their response on the monitoring of hand posture, being these devices designed with dimensions $l = 20$ mm, $h = 3$ mm, $b = 4$ mm and $N = 5$. For the measurement of flexion/extension movements, the transducers were placed on the dorsal side of PIP and MCP joints of index finger, as well as on the thumb IP and MP joints. One may observe that the analysis of index joints could be extended to the middle, ring and little fingers, since they present a similar structure in terms of DOF. With respect to the abduction/adduction of index finger, an additional transducer was attached between the palmar and dorsal sides of MCP joint.

The calibration curves were obtained considering the glove sensor worn by a single subject, by acquiring 600 normalized intensity values per angular position. The user was requested to flex each joint individually according to reference objects manufactured with predetermined angles. These objects were

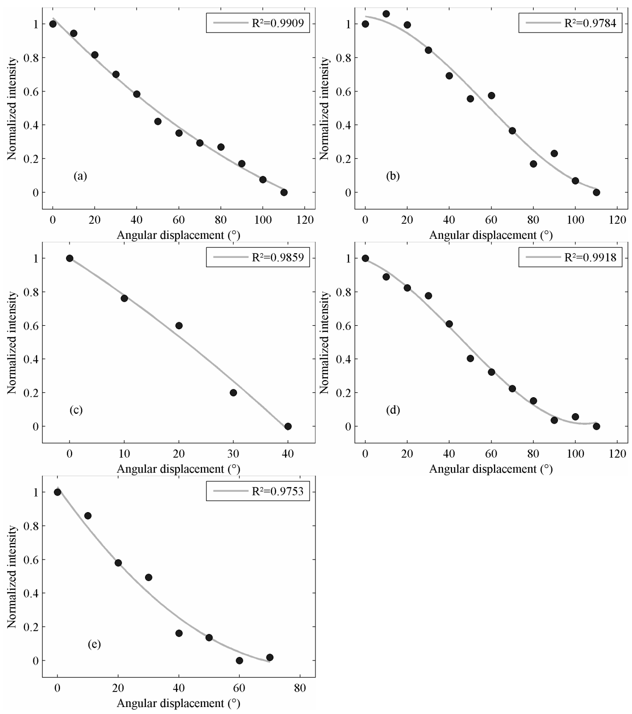

Fig. 5. Sensor response on the variation of angular displacements of finger joints: flexion of (a) PIP and (b) MCP, (c) abduction of MCP joint, and flexion of (d) IP and (e) MP joints. Experimental for (a), (c) and (e) was fitted by 2nd degree polynomial, whereas the data for (b) and (d) was adjusted by 3rd degree polynomials.

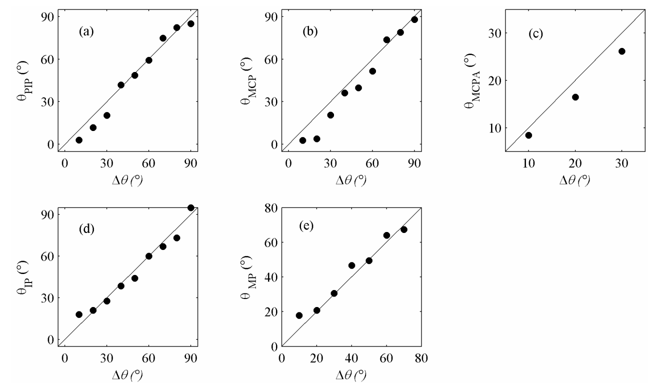

Fig. 6. Comparison of measured and nominal joints angles: index finger (a) PIP, (b) MCP and (c) MCPA joints, and thumb (d) IP and (e) MP joints. The straight lines indicate $\theta = \Delta\theta$.

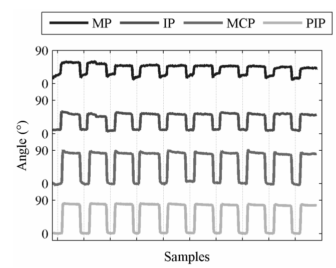

Fig. 7. Measured hand joints angles during the accomplishment of repeatability test for a single trial. The vertical lines indicate the grasping-release events.

designed to fit anatomically to the user fingers, avoiding the influence of excessive mechanical loads during their manipulation.

As illustrated in Fig. 5, the glove sensor presented a reliable response on the measurement of flexion movements of PIP, MCP, IP and MP joints, and abduction of MCP joint (MCPA), regarding the range of angular displacements considered in this study. Eventual differences between transducer characterization and sensor calibration curves can be attributed to the effects of finger geometry and dimensions, even as the mechanical properties of glove material, which could affect the stress application on fiber by microbending mechanism. In case of MP joint, Fig. 5(e), the sensitivity was reduced for larger displacements probably due to the influence of thumb trapeziometacarpal joint movements, since it is relatively difficult to analyze these DOFs separately because of hand motion constraints.

C. Implementation and Validation

In order to evaluate the sensor response on the detection of fingers movements, the system was previously calibrated based on a procedure in which the hand posture is adjusted according to 4 situations. Firstly, all joints are extended in open hand configuration, without abduction or adduction of metacarpophalangeal joints. The user hand is kept static in this position for $\sim$7 s, and a 100 intensity values dataset is acquired for each monitored joint. Subsequently, a visual information is displayed in the GUI asking the subject to move his or her hand to the next configuration, in which the metacarpophalangeal joints are abducted/adducted to the maximum angular displacement with open hand. After that, the same acquisition and position change procedure is repeated, requesting the user to grasp a calibration object in order to adjust the proximal interphalangeal and metacarpophalangeal joints to an intermediary flexion condition. Finally, the subject manipulates another object, which sets the PIP, MCP, IP and MP joints to a more acute flexion. The calibration functions are defined for each joint by considering the nominal angular displacements applied during the different hand configurations, and fitting the acquired intensity values by using polynomial models. The overall calibration procedure is accomplished in less than 1 minute, including the time spent during posture changes and calculations.

For the validation of sensor system, the finger joints were flexed according to predetermined angles based on grasping of reference objects, and the measured angle θ for each position was assumed as the average value of 200 acquisitions, and the measurement errors were evaluated by the absolute difference between nominal displacements $\Delta\theta$ and calculated angles θ. As observed in Fig. 6, the obtained angles are compatible to the nominal ones, resulting in average errors of 4.53° for PIP joint, 6.86° for MCP, 3.67° for MCPA, 3.69° for IP, and 3.33° for MP joint. The discrepancies on MCP results for angular displacements $\leq 30°$ were probably caused by sliding of glove material over the hand back surface, but the eventual wrinkles and gaps are eliminated as fabric is gradually stretched by flexion of index finger, yielding to a more precise

TABLE II
REPEATABILITY ANALYSIS OF THE GLOVE-BASED SENSOR. RANGE AND STANDARD DEVIATION (S.D.) VALUES IN DEGREES. THE REPEATABILITY PARAMETERS WERE FIRST CALCULATED FOR EVERY JOINT IN EACH TRIAL, AND THEN EVALUATED FOR ALL TRIALS

	PIP		MCPF		IP		MP	
Trial	**Range**	**S.D.**	**Range**	**S.D.**	**Range**	**S.D.**	**Range**	**S.D.**
1	4.49	1.62	6.03	1.86	3.73	1.23	6.93	2.35
2	0.37	0.12	7.91	2.76	1.99	0.78	9.97	3.21
3	5.11	1.71	4.13	1.63	7.72	3.00	10.98	3.80
4	4.43	1.47	13.45	5.47	8.71	3.01	13.02	4.84
Mean	3.60	1.23	7.88	2.93	5.54	2.00	10.22	3.55
Trials 1-4	4.08	1.75	10.73	4.95	10.89	4.63	6.53	2.85

response for larger $\Delta\theta$ values. Additionally, the response on MP transducer is slightly affected by the flexion/extension and abduction/adduction of trapeziometacarpal joint of thumb, as previously discussed. This problem could be reduced by changing the position of MP sensor, or even with installation of additional sensors in order to avoid ambiguities on the evaluation of joint angle. Nevertheless, a reduction on the measurement error is also expected in the case of performing a more intensive calibration procedure, by considering additional postures.

D. Repeatability Analysis

The repeatability of the fiber sensor was investigated by carrying out an experiment based on the test proposed by [32]. Once the glove calibration is performed, the male, 28 years old subject is asked to place his or her hand over a flat tabletop, with the joints extended in open hand configuration and the forearm in pronated condition. The user did not present history of orthopedic dysfunctions, and the hand and palm dimensions were 185 and 82 mm, respectively. After receiving a command from the graphical user interface, the subject grasps a mold for ~5 s, being this mold dimensioned in order to adequately adjust to user hand, ensuring that the joints were flexed with the same angular displacement value during the experiments. Finally, the mold is released and the subject returns his hand to the initial condition. The repeatability test was reproduced 4 times, being each trial comprised of 10 grasping-releasing events, by requesting the user to remove and wear the glove again between the experiments. Fig. 7 exemplifies the variations on sensor response for a single trial.

The angular position of each joint during mold manipulation was obtained by calculating the average value of measured angles, resulting in dataset comprising of 10 points per trial. The repeatability was evaluated based on the calculation of the range (difference of maximum and minimum angular displacement value) and standard deviation of each dataset. In addition, this analysis was also applied on the determination of repeatability parameters for all trials. In this case, the average value of each trial was computed, and the range and standard deviation were obtained by considering the mean of angular displacement values.

As shown in Table II, the repeatability parameters of intephalangeal joints were better than that obtained for metacarpophalangeal ones, as well as the analysis of index PIP and MCPF joints yielded to more reliable results in comparison to the thumb IP and MP joints. The abduction movement of MCP joint was not investigated due to the fact that this DOF was not varied in a controlled way during the experiments because of the mold characteristics. One may also observe that the range and standard deviation values are correlated, which corroborates with previous studies [32]. Concerning the overall performance of glove sensor, the average range and standard deviation considering all trials were 8.06° and 3.45°, respectively, which is also consistent to the results obtained by other glove-based devices on the monitoring of the same joints [14], [32], [33]. The increase on range and standard deviation values can be explained by variations on sensor response due to inadequate adjustment of the glove on user hand, which could generate corrugations of glove material over dorsal surface and changes on relative position of fiber transducers, especially for the metacarpophalangeal joints. Another possible source of errors is the effect of mold grasping. Although the experiments were conducted following a strict protocol, it is relatively difficult to make certain that the object was handled exactly in the same way during all trials, causing random variations on hand posture. Moreover, the application of excessive force during the grasping can also affect the measurements, since part of additional mechanical load exerted on the mold is transferred to the microbending transducers.

IV. CONCLUSION

The optical fiber transducer presented a good response on the detection of angular displacements with a simple and inexpensive design, yielding to a sensitivity of ~1.80°. The device was also successfully implemented on a glove-based sensor for real-time measurement of index and thumb fingers movements, presenting average errors $< 5°$ and $< 7°$ for interphalangeal and metacarpophalangeal joints, respectively, with repeatable results. In particular, the sensor performance for metacarpophalangeal joints could be enhanced by optimizing the transducer positioning over the glove, or by applying a more exhaustive calibration procedure. Moreover, even though the system was applied on the monitoring of only 5 joints, this study can be extended to the other fingers due to the similarity and constraints of hand movements. The group is currently working on further developments with focus on the completion of glove-based sensor, and its application in user interfaces for human-robot interaction purposes [34].

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