Force Sensing At the Tip

The Next Step in Surgical Robotics

Why measuring closer to the tool-tissue interaction point matters for safer robotic surgery, better control and AI-assisted systems.

Whitepaper | Resense

Overview

Medical robotics teams are no longer designing systems around motion and visualization alone. As surgical robots become more compact, software-defined and data-driven, developers need reliable information about the physical interaction between instrument and environment.

This whitepaper explains why the next step is not force sensing in general, but force sensing closer to the point where surgical interaction actually happens. Miniature six-axis force/torque sensing can add the missing physical information channel and support three system-level goals: safer procedures and reduced tool-tissue forces, more intuitive robotic control and a physical data layer for future AI-assisted surgical systems.

The focus is practical: which customer function should force data enable, how close to the tool-tissue interaction should it be measured, and how can a near-tip sensing concept move from feasibility testing toward a robust OEM solution?

The relevant measurement point is rarely obvious at the beginning of a project. Force and torque can be captured near the distal instrument tip, within the jaws, the instrument, in a tool adapter or in the drive train, on a robotic arm or at the surgeon console. Each location changes what the signal represents and how much value it can create for control, feedback, monitoring, documentation or AI-supported analysis.

The purpose of this paper is to help teams connect the sensing architecture to the customer function they want to enable. In this context, "at the tip" should be understood as a design direction: moving the measurement as close as technically and economically reasonable to the actual point of contact, so that force data reflects the surgical interaction rather than the accumulated effects of the mechanical chain.

THE CENTRAL QUESTION

Where should force and torque be measured in a surgical robot so that the system receives meaningful information?

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01 Why Medical Robots Need Force Sensing

Force sensing adds the physical information that vision and robot motion alone cannot provide.

A Missing Information Channel

Robotic-assisted procedures combine precise motion, sophisticated visualization and carefully designed workflows. Yet the physical interaction between an instrument and its environment can remain only partially observable. A system may know where an instrument is and how it is moving, while still lacking direct knowledge of what is happening at the point of contact: how much load is applied, whether contact is intentional, and whether resistance comes from tissue interaction, friction, obstruction or unintended preload.

Why Estimation Reaches its Limits

Force is frequently inferred from motor current, kinematic models, observers, or the known behavior of the transmission. These methods can be useful and may be appropriate when the mechanical path is stiff, well characterized and repeatable. The challenge increases in long, cable-driven, flexible, or miniaturized instruments. Friction, hysteresis, play, preload, deformation and external disturbances can accumulate between the actuator and the distal tip. The estimate can then describe the drive train more strongly than the actual interaction.

Direct measurement does not make system modeling obsolete. Instead, it adds a physical reference. It provides measured force and torque information close to the interaction point and can be combined with vision, kinematics, and system models. This is especially relevant when the objective is not merely motion control, but a more complete understanding of contact.

The closer this physical reference is captured to the actual point of contact, the more directly it can support surgical decision-making, control and feedback. This is why near-tip or distal shaft sensing is not only a mechanical integration topic, but a system-design decision: it determines whether the force signal describes the interaction the robot needs to understand or mainly the losses and dynamics between actuator and instrument tip.

COMMERCIAL IMPLEMENTATION

Intuitive's da Vinci 5 introduced Force Feedback technology in a commercial robotic surgery system. According to Intuitive, the technology uses sensors near the instrument tips to allow surgeons to sense push and pull forces; reported preclinical data showed up to 43% less force on tissue in da Vinci 5 tasks. This market example underlines the whitepaper's main argument: moving force sensing closer to the contact point can create measurable system value.[1]

[1] Source: https://www.intuitive.com/en-us/about-us/newsroom/force-feedback

CUSTOMER VALUE

Direct sensing is most valuable when the cost of uncertain interaction is higher than the cost and effort of integration. This can be the case for delicate tissue handling, force-controlled motion, collision monitoring, reproducible testing or high-quality data generation.

Information source	What it primarily reveals	Typical limitation when used alone
Vision	Anatomy, position, scene context and visible deformation	Contact loads may remain difficult to quantify
Kinematics	Position, velocity, orientation and motion state	Physical interaction is inferred through the mechanical chain
Force/torque sensing	Magnitude and direction of forces and torques	Requires a deliberate measurement location and integration concept

Table 1 Comparison of information sources in robotic surgery.

1. Enabling Safer Procedures

Vision describes the scene, kinematics describe motion, and force/torque sensing describes physical interaction. For safer procedures, the value lies in combining these sources so the system can recognize unexpected resistance, contact and overload conditions earlier and more reliably. A measured force signal can support limits, warnings, controlled responses and reduced tool-tissue forces, but it must always be interpreted within the full medical system and validated against the intended use.

2. Enabling Intuitive Robotic Control

Intuitive robotic control depends on the system's ability to translate physical interaction into behavior that feels predictable, responsive and safe to the user. Position and motion data can describe where an instrument is moving, but they do not fully explain how the instrument is interacting with its environment. Force and torque sensing adds this missing layer by showing whether resistance, contact, preload or unintended load is present and how that interaction changes during a movement.

This information can help a robotic system react in a way that is easier to understand and control. Measured interaction forces can be used to scale motion, limit excessive loads, support force-guided movements or provide feedback that reflects the actual contact situation rather than only the commanded motion. The result is a more direct connection between user intention, instrument behavior and physical response at the patient side.

For development teams, the key question is therefore not only where a sensor can be placed, but which control decision the signal should improve. If the goal is more intuitive teleoperation, the force signal must be close enough to the relevant interaction and stable enough to support real-time interpretation. Detailed sensing locations and architecture choices are discussed later in this whitepaper; at this point, the focus is the control value: force information helps the robot respond like an interaction-aware surgical system.

3. Preparing for AI-assisted Surgical Systems

AI-assisted surgical systems need more than images, robot states and commanded motion. They also need direct information about physical interaction: when contact occurs, how strong it is, in which direction the load acts and whether the measured behavior matches the intended surgical task. Force and torque data can add this physical reference channel to development datasets.

This becomes especially relevant for assistance functions such as contact detection, force-aware motion guidance, overload recognition, skill analysis or procedure documentation. Similar visual situations can differ mechanically: an instrument may appear to be in contact with tissue, but only a synchronized six-axis signal reveals whether the interaction is gentle, excessive, axial, lateral or torsional.

In flexible and cable-driven instruments, direct or near-distal force measurement can help separate true tool-tissue interaction from friction, hysteresis, changing curvature and preload in the transmission. When synchronized with vision, kinematics, robot state and user commands, this data supports cleaner event labeling, more reliable model training and a clearer validation path.

DESIGN INSIGHT

Sensing at the tip increases the fidelity of the interaction signal: the closer the measurement is to the tissue contact, the less the signal is affected by friction, hysteresis, compliance or preload in the instrument. The trade-off is integration complexity. Moving the sensor forward increases requirements for miniaturization, hollow-shaft routing, geometric integration, biocompatibility and sterilizability. A useful design frame is therefore: measurement accuracy versus integration complexity.

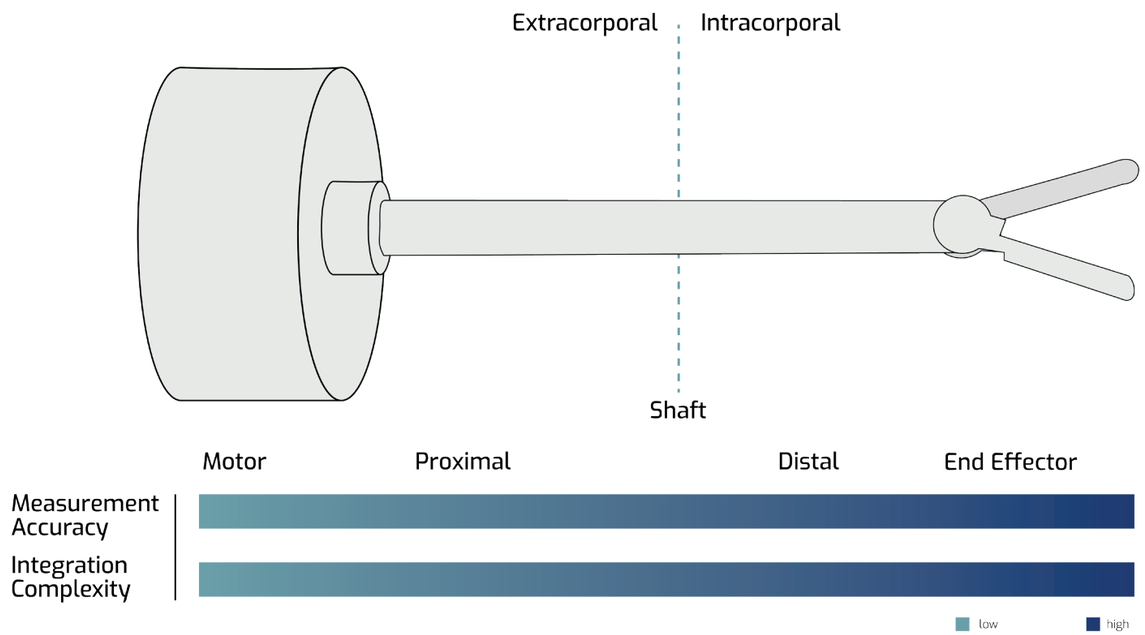
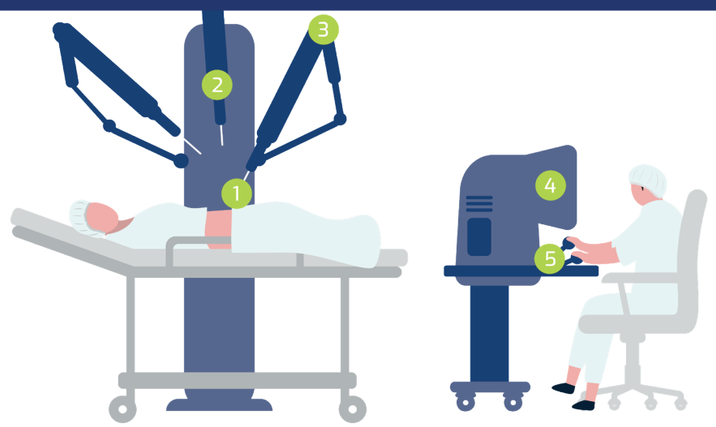


Figure 1 Instrument integration scenarios for force and torque sensors.

02 Where Force/Torque Sensing Creates Value

Customer value depends on measuring close enough to the relevant interaction while preserving instrument function, workflow and lifecycle requirements.



1 Surgical Instrument
2 Instrument Adapter
3 Robot Kinematics
4 Head Console
5 Haptic Input Device

Figure 2 System architecture of a robotic-assisted surgery platform and exemplary force-sensing locations.

1 End-Effector Integration: Directly at the Instrument Jaws

End-effector integration means placing force/torque sensing elements directly in or at the functional tool element, such as a grasper, cutter, needle driver or other task-specific instrument end. This would provide the most direct mechanical view of the actual tool-tissue interaction and can be attractive for highly specific customer architectures. At the same time, it is the most demanding option because it competes with the smallest available space and with core instrument functions such as motion, jaw mechanics, sterility, cleaning, durability and replaceability. For Resense, this should be described as a possible customized concept.

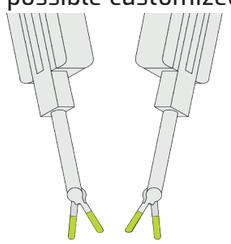


Figure 3 F/T sensor at instrument jaws.

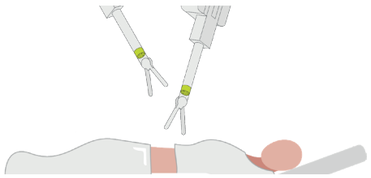


Figure 4 F/T sensor at distal ends of surgical tool.

1 Distal Tool Shaft: Providing Force Signals from the Tip

A shaft distal location places the sensor close to the working end of the instrument, This improves the fidelity of the tool-tissue interaction signal because fewer friction, routing and transmission effects remain between the measurement point and the contact event. It can support overload monitoring, force-controlled motion, and true force feedback.

Compared with shaft proximal sensing, the sensor must fit into a smaller geometry, preserve routing and actuation paths, tolerate local load cases and support the intended cleaning or sterilization.

2 Instrument Adapter: Enabling Smooth Robot Control

In this configuration, the six-axis force/torque sensor is integrated at the instrument adapter interface. This position captures all forces and torques transmitted between the surgical instrument and the robotic system, providing a comprehensive view of instrument interaction.

The approach enables force sensing without modifying the instrument itself and supports rapid integration. While the measurement reflects the loads acting on the complete instrument assembly, mechanical influences between the adapter and the distal tool tip must be considered when interpreting the signals.

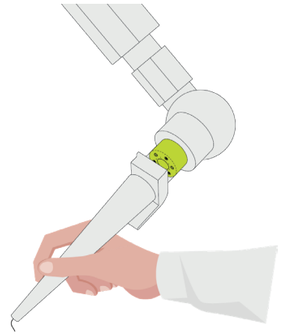


Figure 5 F/T sensor at the instrument adapter.

3 System-Side Sensing: Actuation Unit and Robot Kinematics

Measuring forces and torques at the motor output or along the robot system reduces integration complexity. These positions can support guided motion, collision monitoring, load monitoring, system protection and reusable measurement concepts across different instruments.

The trade-off is signal distance. Measurements at the drive, arm or adapter may include friction, compliance, preload, cable behavior and other mechanical effects before the force reaches the distal instrument tip. They can be highly useful for system monitoring and development, but when the intended customer value is safer tool-tissue interaction or force feedback at the tip, their signal must be interpreted as an indirect representation of the surgical contact.

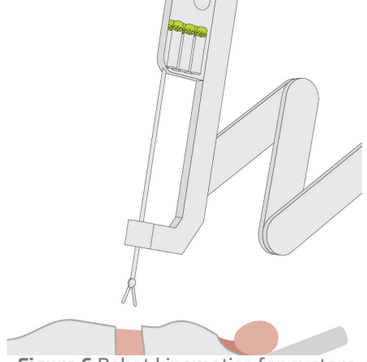


Figure 6 Robot kinematics for system-side sensing.

4 Head Part Sensing: Supporting Control and Ergonomics

Sensors integrated into the head-part provide insight into surgeon interaction and control behavior at the human-machine interface. They can help improve usability, guidance and overall control feel, but they are too far removed from the patient-side contact point to deliver direct information about tool-tissue interaction.

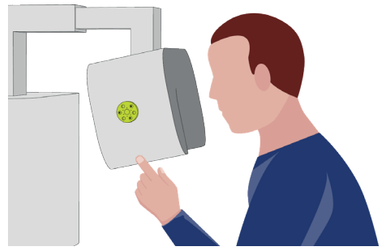


Figure 7 F/T sensor at the head console.

5 Input Device: Measuring Surgeon Interaction

Force/torque sensing in the input device captures how the surgeon interacts with the robotic system. The data reflects user intent, hand forces and ergonomic behavior, supporting intuitive control, console optimization and potential haptic feedback. However, it does not directly measure the forces acting at the surgical tool tip.

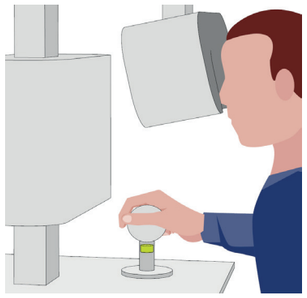
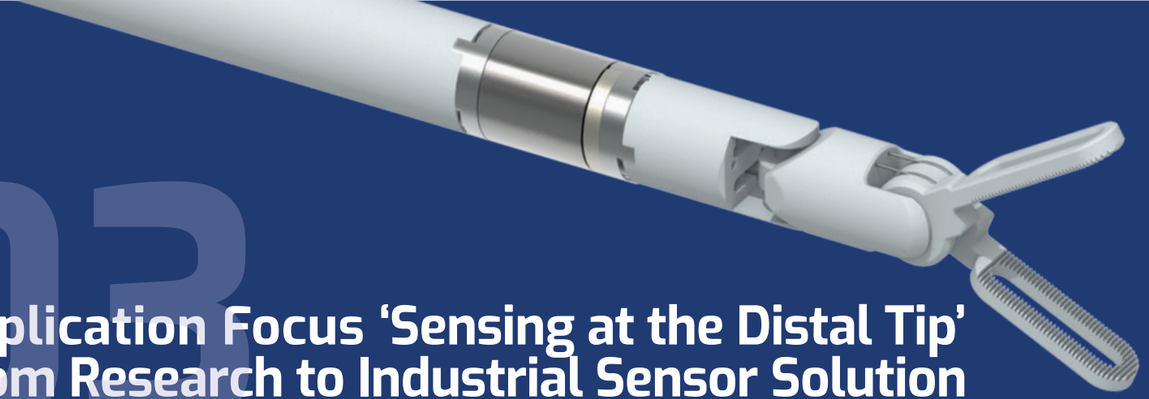


Figure 8 F/T sensor at the input device.



03 Application Focus 'Sensing at the Distal Tip' From Research to Industrial Sensor Solution

Research demonstrates the system value of shaft-integrated force sensing. Industrial adoption depends on whether the same idea can answer customer concerns around sterilizability, mechanical robustness and scalable OEM production.

Research Insight: Why Shaft-Integrated Sensing Matters

The study by Yang et al. (2026)[2], Shaft-integrated Force Sensing with Transformer-based Dynamics Compensation for Telesurgery, addresses a core limitation in telesurgery: commercial robotic instruments often do not provide direct six-axis force sensing at the tool tip. Without this information, distal interaction forces must be estimated from actuator-side signals and robot states, even though friction, cable forces, hysteresis and other nonlinear transmission effects can distort the relationship between motor behavior and true tool-tissue interaction. The research therefore demonstrates why force sensing integrated into or close to the instrument shaft can act as a physical reference for more reliable distal force estimation and control.

The proposed hybrid concept combines three elements: a distal six-axis force sensor integrated into the instrument shaft, robot state information such as position, velocity and torque as model inputs, and a transformer neural network to estimate three-axis distal tip forces. This architecture is important because it does not position direct sensing and model-based estimation as alternatives. Instead, it uses measured force data close to the surgical interaction to compensate for complex system dynamics and improve the quality of estimated tip forces.

According to the case study, the approach achieved force estimation accuracy below 5% compared with baseline setups and showed robust performance across varying conditions, including soft tissue and rigid contact. Its impact lies in safer robotic procedures and improved operator control through force feedback from the distal tip. For this whitepaper, the key insight is that shaft-integrated sensing strengthens both immediate control value and the longer-term data strategy: it provides a more trustworthy physical signal for feedback, validation and AI-supported interpretation of surgical interaction.

From Research Results to Industrial Customer Solutions

For OEM teams, the relevant conclusion is broader than a single accuracy result. Research can demonstrate that shaft-integrated sensing improves force information, but industrial adoption depends on whether the sensor can survive the medical lifecycle, tolerate structural loads, preserve the instrument's functional pathway and be manufactured at scale. This is the point where the discussion shifts from scientific feasibility to a product answer.

[2] Source: https://arxiv.org/abs/2605.31434

Industrial Concerns: What Customers Need to Resolve

Concern 01
Sterilizability
Can the sensor survive repeated cleaning and sterilization cycles?

Concern 02
High Axial Forces
Can the sensor tolerate instrument loads while still measuring sensitively?

Concern 03
Scalability
Can the sensor be produced in high volumes without driving system cost?

Concern 01: Sterilizability

Sterilizability is one of the first questions customers ask because surgical instruments must survive a defined lifecycle, not only a laboratory test. Repeated sterilization can create thermal, mechanical and material stress for the sensor body, bonding, sealing, signal paths and calibration stability. The communication around HEX8 High Force therefore explicitly addresses sterilizability for more than 30 cycles. This does not replace project-specific validation, but it gives customers a concrete starting point: the sensor concept is being developed with repeated reprocessing in mind rather than treated as a single-use laboratory component.

Concern 02: High Axial Forces

High axial load capability is equally critical. In compact instruments, axial loads can arise from insertion, pushing, pulling, tissue interaction, friction in the access path or unintended overload situations. These loads may be much higher than the interaction forces that the system ultimately wants to measure with high sensitivity. A sensor for this environment must therefore combine two properties that are difficult to achieve together: it must remain sensitive enough for meaningful force and torque measurement while providing a robust mechanical load path. HEX8 High Force addresses this concern with a stated axial load capability of Fz greater than 300 N, positioning the concept for applications where mechanical robustness is a prerequisite for integration.

Concern 03: Scalability

Scalability is the third major concern because OEM customers must assess whether a sensor concept can support high annual volumes at a cost level that is viable for the instrument program. A prototype may prove the measurement principle, but it does not answer questions about repeatable assembly, calibration effort, manufacturing yield, supply capability or cost stability.

The case study demonstrates the system value of shaft-integrated sensing, while customers also need confidence that the sensor architecture can move beyond one-off integration without becoming a cost driver. HEX8 High Force is therefore communicated with a mass-production perspective of up to 50,000 units per year. This shifts the discussion from feasibility alone to an industrialization path: how the sensor can be built, tested and supplied repeatedly in a way that supports both volume expectations and target cost corridors.

Product Answer: HEX8 High Force

Figure 9 Resense HEX8 sensor for distal tool integration and high-precision force measurement at the tip.

HEX8 High Force: Built to Fit Your Existing Instrument Design

Available as prototype from Q4/2026

HEX8 High Force is a compact six-axis force/torque sensor concept developed for integration into surgical instruments. It addresses the practical challenge behind distal force sensing: bringing meaningful interaction data closer to the point of contact while preserving instrument architecture, routing and lifecycle requirements.

With prototypes available from Q4/2026, HEX8 High Force gives development teams a concrete starting point for evaluating direct or near-distal force sensing in customer-specific instrument designs. The sensor should be understood as an application-oriented product concept rather than a generic catalogue component. In a customer project, the applicable load case, installation space, routing concept, signal chain, sterilization process and validation plan must be reviewed together with Resense.

Key specification	Description
Outer diameter	8.8 mm
Hollow shaft	Up to 5.5 mm for cable feed-through
Lateral force range	F_x, F_y = 70 N
Axial force capacity	F_z = 250 N
Sterilizability	Developed with sterilization in mind; up to 30 autoclaving cycles
Scalability	Architecture intended for scalable OEM production; up to 50,000 units/year

Table 2 Key Design Targets for the HEX8 High Force.

The HEX8 High Force has been specifically designed for straightforward integration into existing surgical instruments. Its compact 8.8 mm outer diameter and large hollow shaft allow engineers to retain established instrument architectures while providing sufficient space for cable routing.

With an axial force capacity of 250 N, the sensor is robust enough to tolerate the actuation-induced forces within instrument shafts. Integration is achieved through a simple adapter-based concept requiring only minimal design modifications. As a result, development teams can rapidly evaluate force sensing at the distal tip and accelerate the transition from concept evaluation to instrument integration.

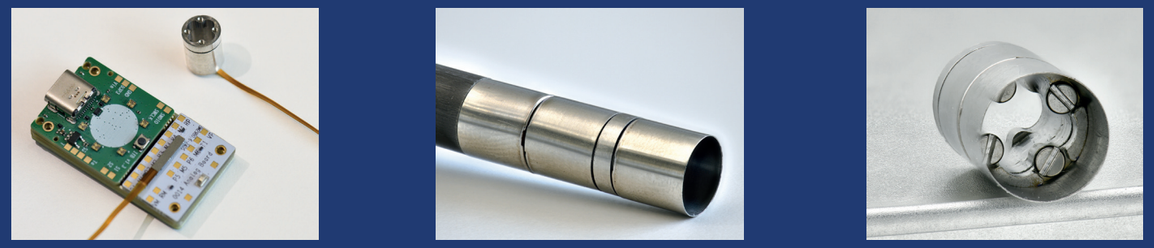


Figure 10 HEX8 High Force prototype and integration concept.

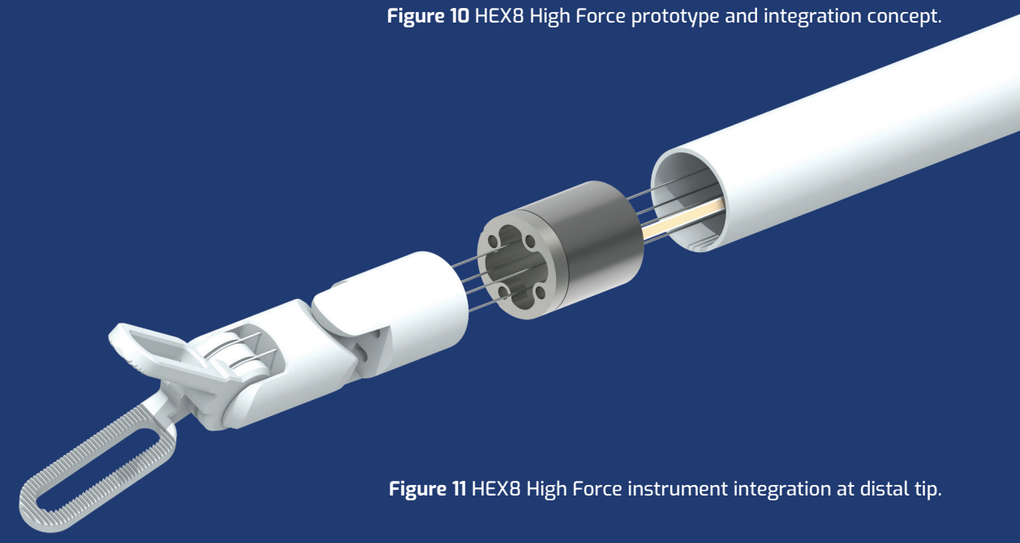


Figure 11 HEX8 High Force instrument integration at distal tip.

04 The Sensing Technology & Product Concept

Miniaturization, silicon strain gauges, modular elementary cells and scalable manufacturing translate system requirements into an integrable sensor.

Strain Gauges for Miniaturization

Resense uses silicon strain gauges as semiconductor-based sensing elements that convert mechanical strain into a change in electrical resistance. Their compact footprint and sensitivity support sensor architectures in which measurement elements must fit into highly constrained mechanical structures. In the product concept, the sensing element is only one part of the system; mechanics, electronics, software and calibration determine whether the signal can become reliable force information for the customer application.

Modular Design by Elementary Cells

A central design principle is the elementary cell: a standardized unit that includes the sensing element and serves as a building block for different sensor architectures. This modular approach helps Resense adapt proven measurement principles to customer-specific load cases, geometries and routing requirements without treating every OEM request as a completely new system.

Scalable Processes for High Volumes

Planar manufacturing creates elementary cells using two-dimensional processes on flat substrates before they are assembled into three-dimensional sensor systems. Combined with automated bonding and pick-and-place processes, this approach is designed to support repeatability and future scaling. The customer benefit is not the manufacturing method itself. It is the possibility of developing a compact OEM sensor without relying on a purely manual, one-off production concept.

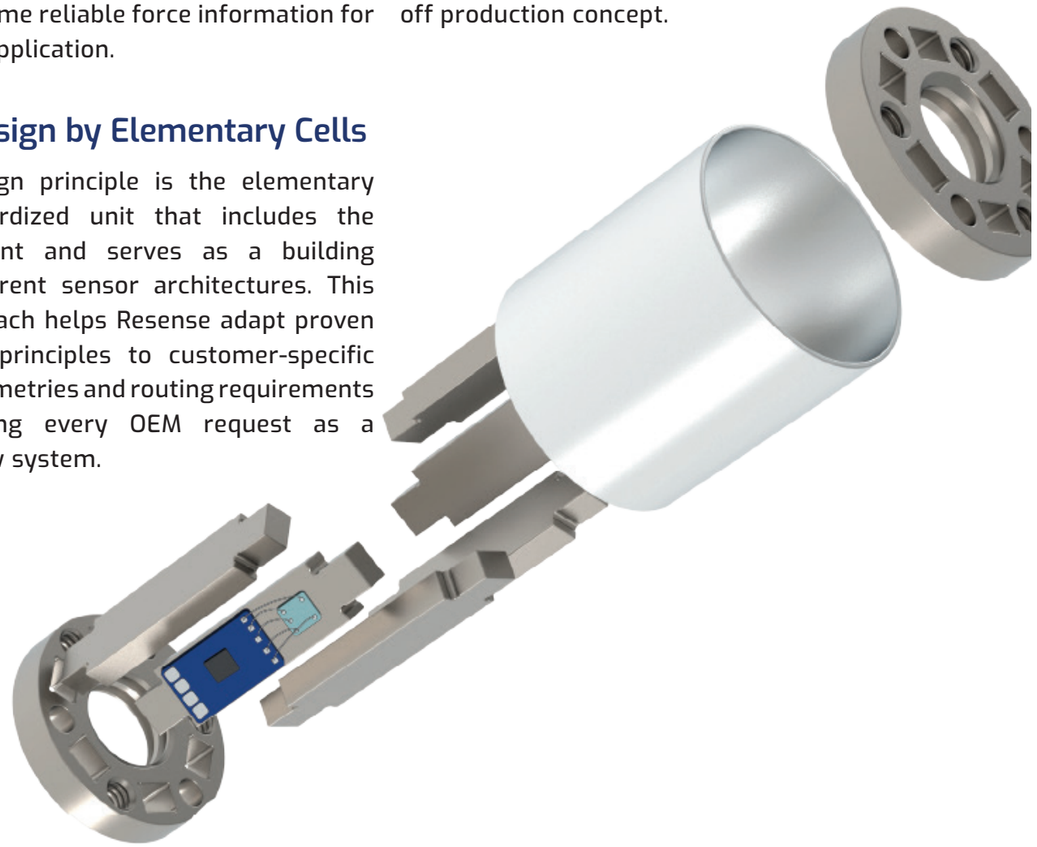


Figure 12 Technology modules: Si straing gauges, 25 µm wire bonding and integrated electronics.

Figure 13 Resense runs scalable production processes at the WIKA Headquarters in Klingenberg including laser welding, autoclaving, and growth-ready manufacturing capacities.

The HEX Sensor Kit as Exploration Platform

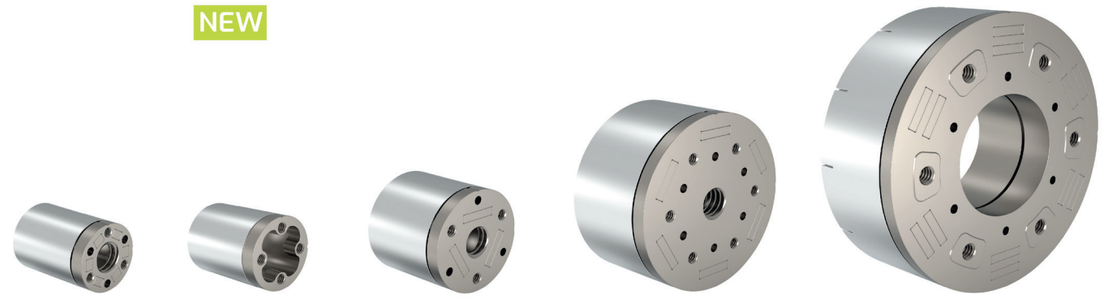
The Resense HEX Sensor Kit combines a six-axis F/T sensor, an electronics box and software for operation and evaluation. Portfolio sensors cover several sizes and force ranges and provide a ready-to-use path for initial testing, data collection and proof-of-concept work.

The kit can help teams validate where force information creates value before committing to an application-specific mechanical integration.

By enabling rapid experimentation with real-world applications, it reduces development risk and helps establish clear performance requirements for future custom OEM sensor solutions.

F/T Sensors

HEX 8	HEX 8 High Force	HEX 12	HEX 21	HEX 32
Ø 8.4 mm	Ø 8.8 mm NEW	Ø 12.5 mm	Ø 21 mm	Ø 32 mm
F = 25N	Fz = 250N	F = 25N	F = 50N	F = 125N



Miniature Electronics Box

F/T Explorer Application Software

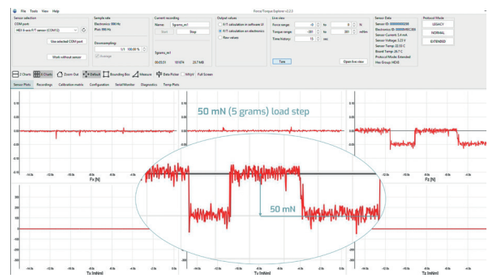


Figure 14 Resense F/T sensor portfolio and ready-to-use kit.

05 From Feasibility to an OEM Sensor Solution

Customized OEM sensors follow a staged path: clarify the application, prove the value, translate requirements into a sensor architecture, validate samples and prepare scalable production.

01 Define

Use case, force information, customer value

02 Prove

Sensor kit, test setup, signal relevance

03 Design

Load case, geometry, electronics, lifecycle

04 Validate

Samples, measurements, design risks

05 Scale

Manufacturing, calibration, supply concept

Figure 15 OEM sensor solution process at Resense.

A Staged OEM Sensor Process

Developing a successful OEM sensor solution requires a structured process that balances technical validation with commercial risk reduction. Beginning with a clear definition of the application, each stage builds confidence in the measurement concept before advancing to the next level. Through feasibility studies, sensor design, prototype validation, and preparation for serial production, decision gates ensure that critical requirements are met and risks are addressed early. This staged approach helps transform application-specific force and torque measurement needs into reliable, scalable OEM products ready for industrial deployment.

Decision Gates Along the Way

Gate	Key question	Output
Value gate	Does force/torque data improve a defined customer function?	Measurement objective and success criteria
Concept gate	Can the sensor architecture fit geometry, load case and lifecycle?	Requirements baseline and sensor concept
Sample gate	Do measured samples confirm functionality and design direction?	Validated direction and risk list
Scale gate	Can manufacturing, calibration and supply be repeated reliably?	Production-intent plan

Table 3 Decision gates from concept to production.

06 Outlook

Force/torque data can become a structured physical data layer for validation, assistance functions and future AI-supported systems.

Data Strategy: Turning Force Signal into System Knowledge

In the near term, the key question is whether F/T sensing improves a defined customer function: safer interaction, better feedback, controlled motion or reproducible testing. Over time, the same signal can create additional value when it is captured consistently, synchronized with vision, kinematics, instrument state and user commands, and interpreted in the context of the surgical task.

This perspective should remain forward-looking. It may support event labeling, force-aware datasets, skill analysis, procedure documentation and the validation of AI-assisted functions, but requires application-specific validation, traceable data quality and close cooperation with system developers.

The Future of Meaningful Force Data

Medical robotics is moving toward richer perception, interaction-aware control and increasingly capable assistance functions. In that environment, F/T sensing turns physical interaction into information for surgeons, controllers, developers and future algorithms.

The central question therefore returns at the end of every development path: where should force and torque be measured in a surgical robot so that the system receives meaningful information?

The strongest opportunity is to move measurement closer to the actual point of interaction: from shaft proximal toward shaft distal or, where appropriate, end-effector integration. This strengthens both the immediate customer value and the long-term data strategy, because force data becomes more meaningful when it is close enough, stable enough and contextualized enough to describe real interaction. Miniature sensor technology is therefore not the goal in itself; the goal is moving force data to the place where the robotic system can understand, respond to and eventually learn from the forces that shape its performance.

CLOSING THOUGHT

Machines already see and move with extraordinary precision. Direct force and torque sensing gives development teams the missing physical context to design systems that can also feel.

About Resense

Resense GmbH develops miniature force and torque sensing solutions for demanding robotic applications. The company combines application know-how, sensor-system competence and scalable manufacturing technologies. Its portfolio includes miniature six-axis F/T sensors and customized OEM sensors based on silicon strain gauges, modular sensor architectures and integrated system components.

Resense is a joint venture of WIKA and WITTENSTEIN. The company's vision is to enable machines to feel and thereby create innovation for its customers. Resense focuses on compactness and precision and supports applications in medical, industrial and service robotics.

Terminology

Term	Meaning in this paper
F/T sensor	A force/torque sensor capable of measuring forces and torques simultaneously; in the Resense context, typically in six axes.
Force feedback	The transmission of force-related information from a machine or environment to a user or control system.
Hollow shaft	A central structural opening designed to route cables, tubes or other components through the sensor assembly.
Elementary cell	A standardized unit including the sensing element that serves as a building block for different sensor architectures.
OEM	Original Equipment Manufacturer are companies that integrate force/torque sensors into their end products and bring these products to market.
Under development	A product, feature or technology currently being designed, tested or refined prior to release.

Editorial Note

This document is written as an external marketing whitepaper. Development concepts and future specifications are marked accordingly. Product selection and claims for a specific medical application require project-specific technical, regulatory and lifecycle evaluation.

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