# BarrettHand Grasper: Programmably Flexible Part Handling and Assembly

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## Contents




**Abstract**

This paper details the design and operation of the BarrettHand TM BH8–282, an intelligent, highly flexible eight-axis gripper that reconfigures itself in real time to conform securely to a wide variety of part shapes without tool-change interruptions. The grasper brings value to automation because it: reduces the required number and size of robotic workcells while boosting throughput; consolidates the hodgepodge proliferation of customized gripper-jaw shapes onto a common programmable platform; and enables incremental process improvement and accommodates frequent new-product introductions, capabilities deployed instantly via software across international networks of factories.



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A. Goswami, P. Vadakkepat (eds.), *Humanoid Robotics: A Reference*,
https://doi.org/10.1007/978-94-007-6046-2_87

## 1 Introduction

This paper introduces an approach to material handling, part sorting, and component assembly called "grasping," in which a single reconfigurable grasper with articulated fingers and embedded intelligence replaces an entire bank of unique, fixed-shape grippers, and tool changers.

Robotic Hands with articulated fingers have been around since at least the 1970s. The initial BarrettHand, developed in the early 1990s, was based on mechanisms/kinematics built into the PennHand, designed by Nathan Ulrich, under the supervision of Ruzena Bajcsy, both then at the University of Pennsylvania. But many other hands such as Ken Salisbury's SalisburyHand, developed at Stanford University, strongly influenced the design of the BarrettHand (Figs. 1 and 2).

To appreciate the motivations that guided the design of the BarrettHand, we must explore one of the most challenging aspects in robotics, namely, where the robot must conform and interact with its environment. For the benefits of a robotic solution to be realized, programmable flexibility is required along the *entire* length of the robot, from its base, all the way to the point of physical interaction with the world. A robot arm enables programmable flexibility from the base only up to the toolplate, a few centimeters short of the target workpiece. But these last few centimeters of a robot must adapt to the complexities of securing a new object on each robot cycle,


**Fig. 1** The BarrettHand BH8–282

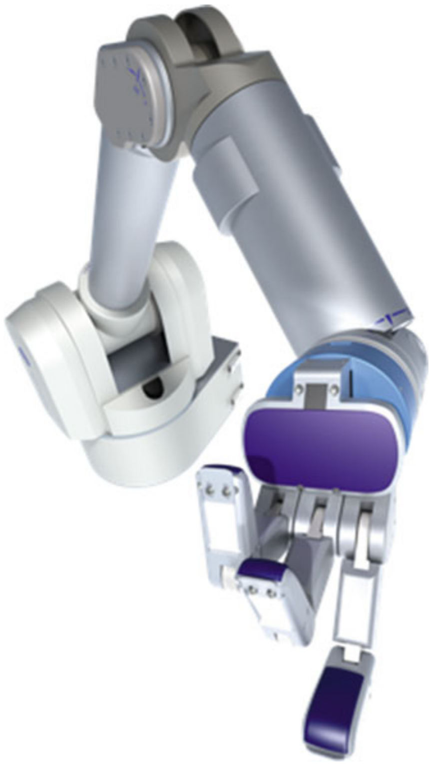

**Fig. 2** BarrettHand™ BH8–282 mounted on a dexterous WAM® arm

capabilities where embedded intelligence and software excel. Like the weakest link in a serial chain, an inflexible gripper limits the productivity of the entire robot.

Grippers have individually customized, but fixed, jaw shapes. The trial-and-error customization process is design intensive, generally drives cost and schedule, and is difficult to scope in advance. In general, each anticipated variation in shape, orientation, and robot approach angle requires another custom-but-fixed gripper, a place to store the additional gripper, and a mechanism to exchange grippers. An unanticipated variation or incremental improvement is challenging.

By contrast, the mechanical structure of the BarrettHand, illustrated in Fig. 3, is automatically reconfigurable and highly programmable, matching the functionality of virtually any gripper shape or fixture function in less than a second without pausing the workcell throughput to exchange grippers.

For tasks requiring a high degree of flexibility such as handling variably shaped payloads presented in multiple orientations, a grasper is more secure, quicker to install, and more cost-effective than an entire bank of custom-machined grippers with tool changers and storage racks.

**Fig. 3** Graspers automatically conform to any part shape in any orientation

For uninterrupted operation, just one or two spare graspers can serve as emergency backups for several hundred workcells, whereas one or two spare grippers are required for each gripper variation – potentially dozens per workcell. And, it is catastrophic if both gripper backups fail in a gripper system, since it may be many hours before replacements can be identified, custom shaped from scratch, shipped, and physically replaced to bring the affected line back into operation. By contrast, since graspers are physically identical, they are always available in unlimited quantity, with all customization provided instantly in software.

## 2 Gripper Legacy

Most of today's robotic part handling and assembling is done with grippers. If surface conditions allow, vacuum suction and electromagnets can also be used, for example, in handling automobile windshields and body panels. As part sizes begin to exceed the order of 100 gms, the jaws of a gripper are custom shaped to ensure a secure hold. As the durable mainstay of handling and assembly, these tools have changed little since the beginning of robotics many decades ago.

Grippers, which act as simple pincers, have either two or three unarticulated fingers, called "jaws," which either pivot or remain parallel during open/close motions as illustrated in Fig. 4. Well organized catalogs are available from manufacturers that guide the integrator or customer in matching various gripper components (except naturally for the custom jaw shape) to the task and part parameters.

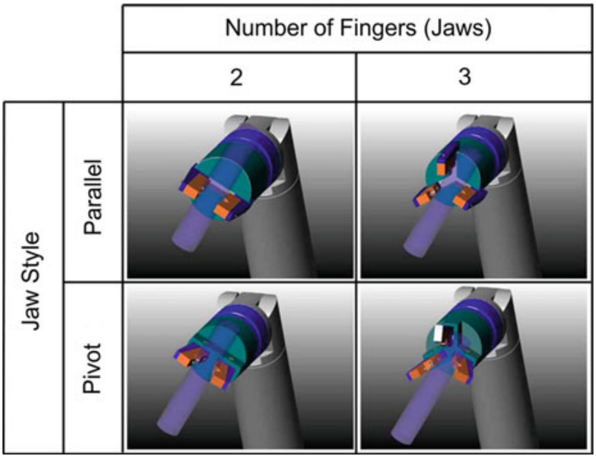


**Fig. 4** Gripper styles are limited. Adaptability is accomplished mechanically, not via software, which is the point of robotics

## 2.1 Unusual Importance of *Hand Height*

Before delving into details of a robotic hand, it is important to consider the robot hand-arm system as a whole. The distance between the kinematic center of the wrist joint and the center of the grasped object is called the wrist offset. In humans, this distance is only a few centimeters. In robots, this distance tends to be much larger, with detrimental effects. The taller the hand the greater the contribution to the wrist offset. The dexterity of the hand should never be considered in isolation. Ultimately, the hand-arm *system* dexterity is more important. Hand height is especially a problem with today's smart graspers where the generally bulky motor-controller electronics are housed between the wrist and the center of grasp. The wrist offset is dramatized in Fig. 5, with a smaller offset (left) and a larger offset (right), each reorienting the grasped object by the same 270°. The issues regarding this offset may not be well recognized until long after the purchase decision has been made for the arm and for the hand, each considered in isolation. However, when considered as a *complete system*, the following issues arise with larger offsets:

- Reduced volume of dexterous workspace
- Joint limits reached more quickly
- Increased likelihood of collisions
- Increased momentum in case of a collision
- Higher power required for the same object rotation rate
- Speed, acceleration saturate more quickly
- Increased torque load on (weaker) wrist motors

An advantage of the BarrettHand is leveraging of the Puck®, which is (by an order of magnitude) the world's smallest servomotor controller weighing in at an

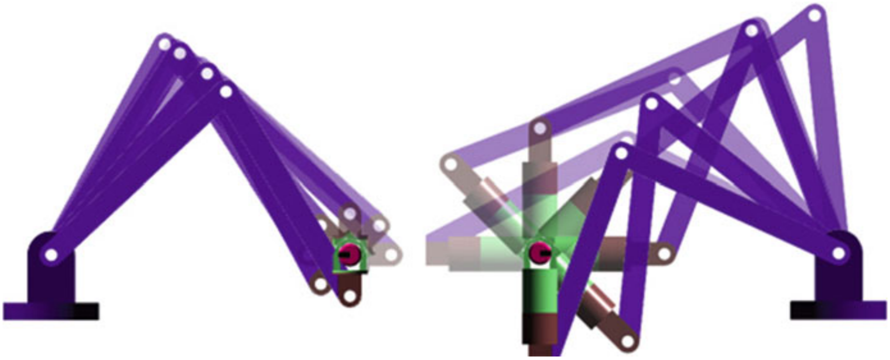

**Fig. 5** Effect of added hand height reduces arm workspace and arm dexterity

almost unbelievably small 2.5 g. The Puck has enabled the height of the palm, where the electronics live, to be reduced to only a few millimeters. When combined with a robot where the contribution to wrist offset, like Barrett's WAM® arm or KUKA's iiwa® Lightweight arm, has been minimized, the *system* dexterity becomes spectacular.

## 3 Description of the BarrettHand

### 3.1 Flexibility and Durability in a Compact Package

The flexibility of the BarrettHand is based on the articulation of the eight joint axes. Only four brushless DC servomotors are needed to control all eight joints, augmented by intelligent mechanical coupling known as Barrett's TorqueSwitch™. The resulting 980-g grasper is completely self-contained with only a 6-mm-diameter umbilical cable with four conductors supplying DC power and establishing a two-way communication link to the main robot controller of the workcell. The grasper's electronics are based on an arrangement of four of its ultraminiature Puck® motor controllers. Each 2.5-g Puck is an all-in-one one-per-servomotor device (so there are four) and embodies communications electronics, multiple microprocessors, memory, sensors, signal-processing electronics, electronic commutation, current amplifiers, and brushless servomotors. The ultraminiature size of Pucks enables the very slim/short BarrettHand base which minimizes the offset between the kinematic center of the wrist and the center of grasp.

The BarrettHand has three articulated fingers and a palm which act in concert to trap the target object firmly and securely within a grasp consisting of seven coordinated contact vectors — one from the palm plate and one from each link of each finger.

Each of the BarrettHand's three fingers is independently controlled by one of three servomotors. Except for the spread action of fingers Fl and F2, which is driven by the fourth and last servomotor, the three fingers, Fl, F2, and F3, have inner and outer articulated links with identical mechanical structure.

Each of the three finger motors must drive two joint axes. The torque is channeled to these joints through a patented, TorqueSwitch™ mechanism, whose function is optimized for maximum grasp security. When a fingertip, not the inner link, makes first contact with an object, it simply reaches its required torque, locks both joints, switches off motor currents, and awaits further instructions from the microprocessors inside the BarrettHand or a command arriving across the communications link.

But, when the inner link makes first contact with an object for a secure grasp, the TorqueSwitch reaches a preset threshold torque, locks that joint against the object using a shallow-pitch worm drive, and redirects all torque to the fingertip to make a second, enclosing contact against the object within milliseconds of the first contact. The sequence of contacts is so rapid that you cannot visualize the process without the aid of high-speed photography. After the grasper releases the object, it resets the TorqueSwitch threshold torque for each finger in anticipation of the next grasp by opening each finger against its mechanical stop with a controlled torque. The higher the opening torque, the higher the subsequent threshold torque. In this way, the grasper can accommodate a wide range of objects from delicate, to compliant, to heavy.

The finger articulations, not available on conventional grippers, allow each digit to conform uniquely and securely to the shape of the object surface with two independent contact points per finger. The position, velocity, acceleration, and even torque can all be processor controlled over the full range of 200,000 encoder positions. At maximum velocity and acceleration settings, each finger can travel full range in either direction in less than 1 s. The maximum force that can be actively produced is 20 N, measured at the tip of each finger. Once the grasp is secure, the links automatically lock in place allowing the motor currents to be switched off to conserve power until commanded to readjust or release their grasp.

While the inner and outer finger-link motions curl anthropomorphically, the spread motion is distinctly nonanthropomorphic. The spread motion is closest in function to a primate's opposable (thumb) finger, but instead of one opposable finger, the BarrettHand has twin, symmetrically opposable fingers centered on parallel joint axes rotating 180° around the entire palm to form a limitless variety of gripper-shapes and fixture functions.

The spread can be controlled to any of 35,000 positions over its full range in either direction within 1/2 s. Unlike the mechanically lockable finger-curl motions, the spread motion is fully backdrivable, allowing its servos to provide active stiffness control in addition to control over position, velocity, acceleration, and torque. By allowing the spread motion to be compliant while the fingers close around an object, the grasper seeks maximum grasp stability as the spread accommodates its position, permitting the fingers to find their lowest energy states in the most concave surface features.

## 4 TorqueSwitch™

Intelligent, dexterous control is key to the success of any programmable robot, whether it is an arm, automatically guided vehicle, or dexterous hand. While robotic intelligence is usually associated with processor-driven motor control, many biological systems, including human hands, integrate some degree of specialized reflex control independent of explicit motor-control signals from the brain. In fact, the BarrettHand combines reflexive mechanical intelligence with programmable microprocessor intelligence for a high degree of practical dexterity in real-world applications.

By strict mathematical definition, dexterity requires independent, intelligent motor control over each articulated joint axis. For a robot to be dexterous, at least $n$ independent servomotors, and sometimes as many as $n + 1$ or $2n$, are required to drive $n$ joint axes. Unfortunately, servomotors constitute the bulkiest, costliest, and most complex components of any dexterous robotic hand. So, while the strict definition of dexterity may be mathematically elegant, it leads to impractical designs for any real application.

Per the definition, neither your human hand nor the BarrettHand is dexterous. Naturally, their superior versatility challenges the definition itself. If the BarrettHand followed the strict definition for dexterity, it would require between eight and 16 motors, making it far too bulky, complex, and unreliable for any practical application outside the mathematical analysis of hand dexterity. But, by exploiting four intelligent, joint-coupling mechanisms, the almost-dexterous BarrettHand requires only four servomotors (Figs. 6 and 7).

It is easiest to understand Barrett's TorqueSwitch™ mechanism by first understanding the operation of the BarrettHand finger assembly. Figure 8 shows a single finger, including all critical drive elements, with the motor windings and rest of the BarrettHand hidden.

Figure 9 is a close-up of the drive elements in the finger. During normal operation, the 16-tooth motor pinion (gray) drives both the 30-tooth distal (yellow) and 40-tooth proximal (blue) gears, which transmit power through their respective

**Fig. 6** Grasping a tube (*left*) and a medical plasma bag (*right*)

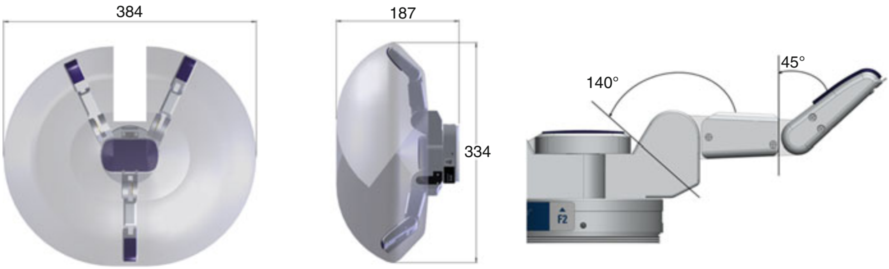


**Fig. 7** Workspace of the BarrettHand

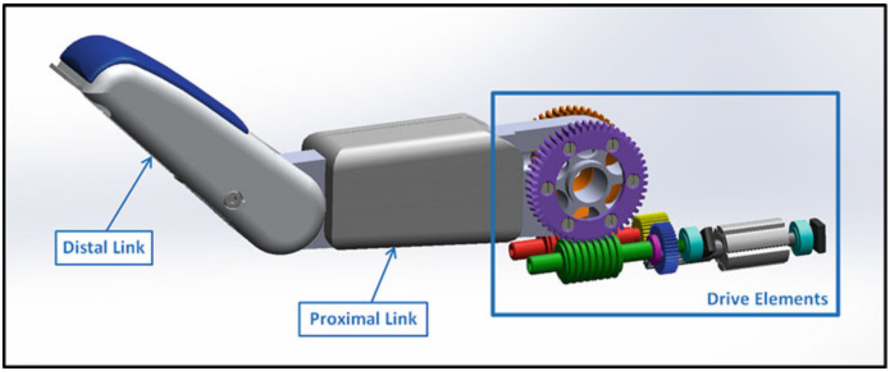


**Fig. 8** BarrettHand finger modular unit, removed from the base of the hand with a single screw

right-handed, single-start worms (red and green), and into two 50-tooth worm gears (orange and purple). The proximal worm gear (purple) is tied directly to the proximal link with six screws, whereas the distal gear (orange) connects to the distal link via mechanical cables (hidden in this view, but visible in Fig. 16). The net result is a motion ratio of 93.75:1 for the motor shaft to proximal joint position and a 125:1 reduction for the motor shaft to distal joint position. Also, note the two magnets (light blue) and their associated Hall-array sensors (black) at the ends of the motor shaft and worm shaft. The magnets are magnetized N/S radially, rather than axially, which allows the Puck (motor controller) to determine the position of both joints in the finger via the Hall-array sensors.

The connection between the proximal worm (green), the Belleville washers (purple) and the proximal gear (blue) is the critical part of this assembly that makes the TorqueSwitch™ work. The proximal gear is internally threaded, and rides on right-handed threads cut into the worm shaft, while the Belleville washers are compressed between the side of the gear and a shoulder on the shaft. The compressed Bellevilles maintain Coulomb friction in the assembly that holds the gear stationary relative to the worm.

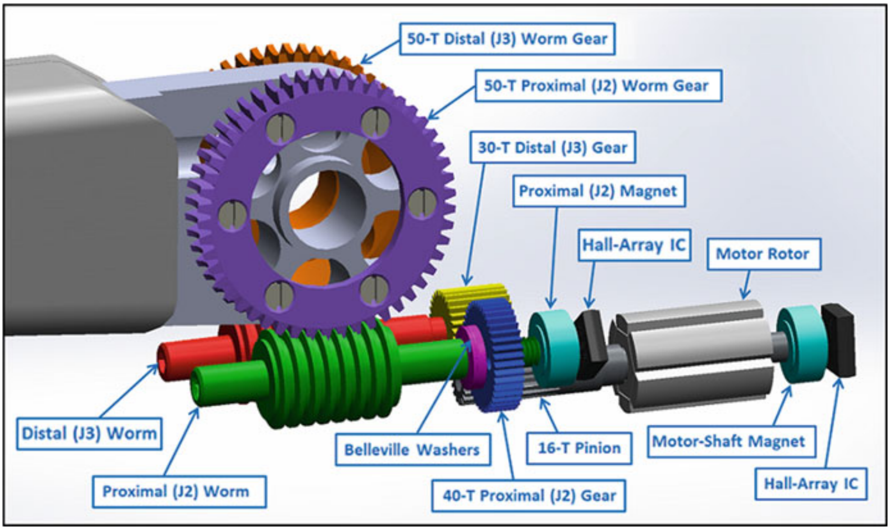


**Fig. 9** Drive elements in the finger of a BarrettHand

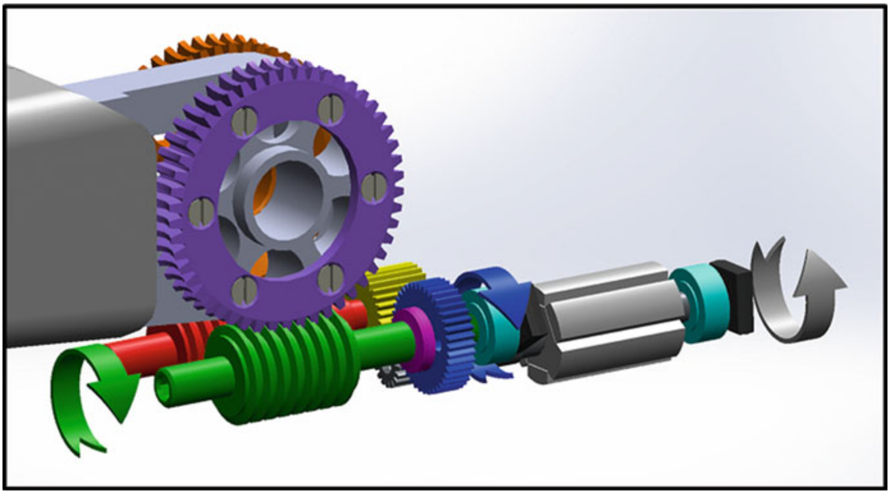

**Fig. 10** State of drivetrain before breakaway

When the proximal link contacts a surface, the resultant torque in the worm causes the gear to "break away" from the Coulomb friction and wind off the washers along the shaft. Figures 10, 11 and 12 show this process.

In some instances, reflex control is even better than deliberate control. Two examples based on your own body illustrate this point. Suppose your hand accidentally touches a dangerously hot surface. It begins retracting itself instantly, driven by local

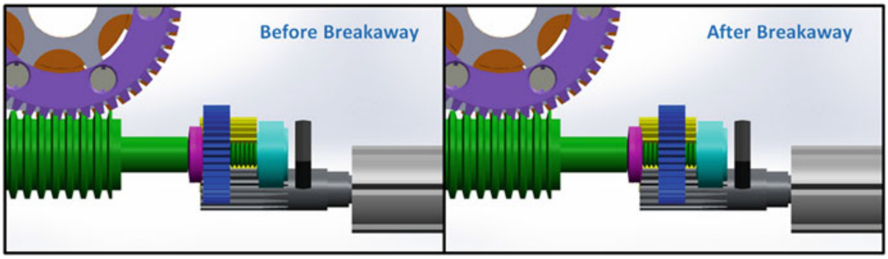


**Fig. 11** Proximal gear releases from the Belleville washers

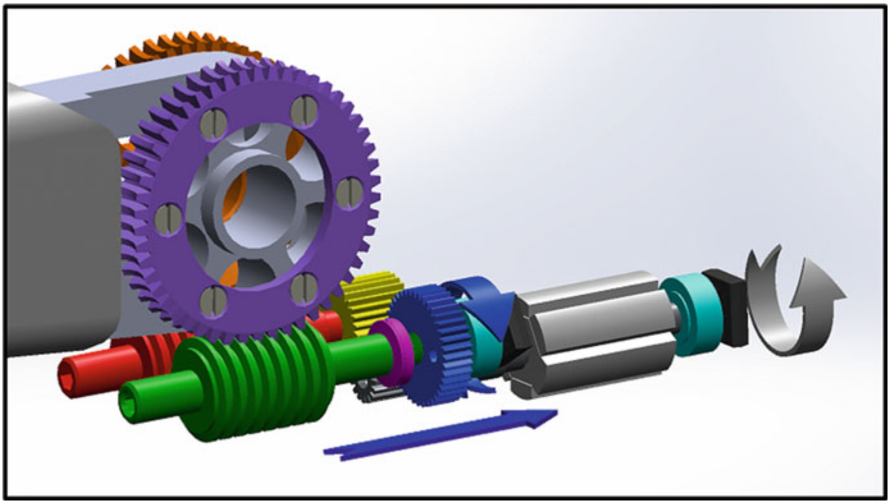

**Fig. 12** State of drivetrain after breakaway

reflex to override any ongoing cognitive commands. Without this reflex behavior, your hand would burn while waiting for the sensations of pain to travel from your hand to your brain via relatively slow nerve fibers and then for your brain, through the same slow nerve fibers, to command your arm, wrist, and finger muscles to retract.

As the second example, try to move the outer joint of your index finger without moving the adjacent joint on the same finger. If you are like most people, you cannot move these joints independently because the design of your hand is optimized for grasping. Your muscles and tendons are as streamlined and lightweight as possible without forfeiting functionality.

The design of the BarrettHand recognizes that intelligent control of functional dexterity requires the integration of microprocessor and mechanical intelligence.

# 5 Sensing Options

Several sensor packages are available with the BarrettHand. Three packages will be discussed here. These packages can be used separately or in any combination. They include tactile sensing, the PerceptionPalm, and the fingertip-torque sensor. There is also a 12-mm-short 6-axis force-torque sensor that is at once modular *and* fully integrated (mechanical, electronics, software) when attached.

## 5.1 Tactile-Sensing Package

The BarrettHand can be purchased with tactile sensing in which 24 individual sensor pads are provided for each fingertip and for the palm (Fig. 13). The sensor pads are based on measuring the resistance across resistive ink between a Mylar sandwich and protected by a pad of Urethane that has been optimized for successful grasping strategies. While the sensor pads on the palm are of equal areas, the pads on the fingertips become smaller (and therefore more precise) at the very tip of the fingertips.

## 5.2 PerceptionPalm™ Sensor Package Option

The PerceptionPalm (US Patent No. 7,168,748) sensor package (right) is the latest sensor option offered by Barrett Technology. The PerceptionPalm adds valuable close-range localization information for making real-time grasping decisions.

The PerceptionPalm sensor package (Fig. 14) contains four elements: (1) white LED for illumination, (2) laser module with diffractive optic element for structured-light pattern projection, (3) Sharp GP2Y0E03 IR rangefinder with 4–50 cm range, and (4) two e-CAM 21 USB Camera modules streaming 320x240 video at 30 FPS, one equipped with a Gorilla Glass clear window (4a) and the other equipped with a 660-nm bandpass filter to maximize laser visibility (4b). The cameras can also take snapshots at 1600x1200. All the PerceptionPalm sensors operate over a single

**Fig. 13** Tactile sensing arrays on the palm and fingertips

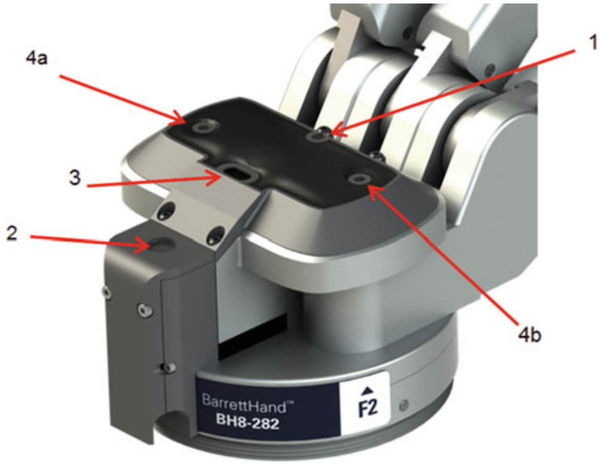


**Fig. 14** PerceptionPalm™ with vision, laser range finder, structured-light projection, and white LED

USB 2.0 connection and communicate via ROS. This compact sensor package provides researchers the hardware to develop their own algorithms for endpoint localization, object recognition, detailed depth perception, and 3D scene mapping (Fig. 15).

Additionally, the BH8–282 with PerceptionPalm maintains a very low profile, increasing the wrist offset by only 6 mm. The PerceptionPalm can be combined with other optional sensor packages, so that each finger can contain a 0.04-Nm-resolution fingertip torque sensor and a 0.01-N-resolution tactile pressure sensor array. Without relying on any of the sensor packages, the underactuated fingers passively conform to objects and the two outer fingers can swing 180° to change finger positions from opposed to aligned. This compact package results in maneuverability and dexterity in constrained environments.

## 5.3 Strain-Gage Fingertip Torque Sensor

The fingertip torque sensor exploits the cable transmission that carries torque from the finger base to the fingertip. A wheel (the brown wheel in Fig. 16, right) with a diameter slightly larger than the distance between the opposing drive cables forces each cable slightly off its straight-line path. When no torque is applied, the wheel is perfectly balanced between these two cables. When a positive torque is applied from Force A, the top cable begins to straighten while the bottom cable relaxes, forcing the wheel (which is supported on a flexible beam) downwards. When the beam flexes, the strain gages, arranged electrically in a Wheatstone bridge bonded to the beam, stretch and contract. The resistance changes are measured in real time and reported to the electronics in the hand and communicated externally to the hand as torques.

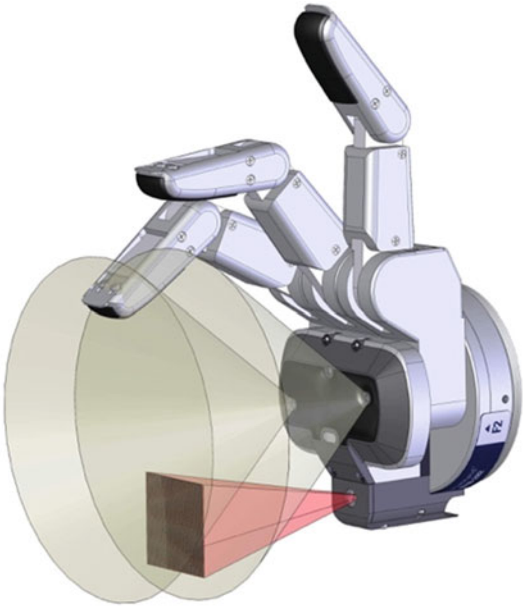

**Fig. 15** This graphic illustrates roughly the spread angles of the video cameras and the structured light projection. The spread of the white LED is not shown here

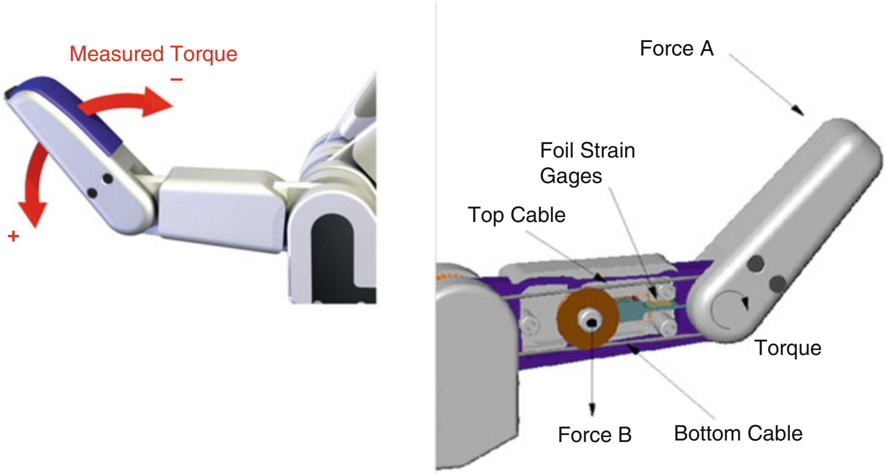


**Fig. 16** Fingertip torque sensor

## 5.4 Control Electronics

Inside its compact palm, the BarrettHand contains four motion-control microprocessors which communicate to the workcell PC or controller by using the same industry-standard CANbus technology used in modern cars. CANbus has several advantages: highly robust, only two conductors, and fast. Associated with each motion-control microprocessor are the related sensor electronics, motor-commutation electronics, and motor-power current-amplifier electronics for that finger or spread action.

## 5.5 Control Software

The BarrettHand Control GUI (Figs. 17, 18, 19 and 20) offers the ability to test various grasping methods quickly and easily. As soon as a reliable grasp configuration is found, the Control GUI generates the code necessary to repeat

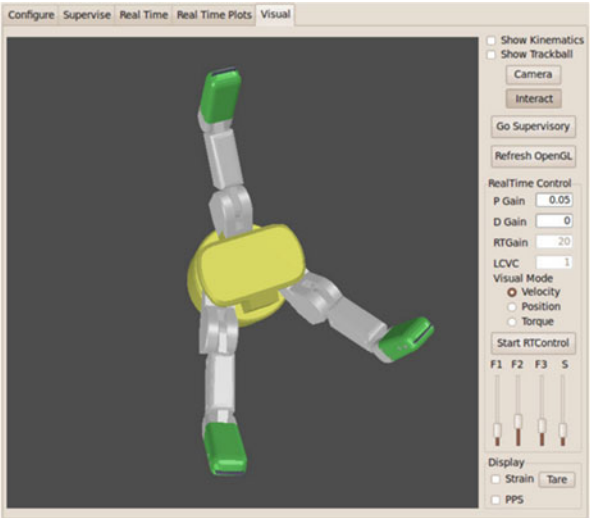


**Fig. 17** Visual control, an intuitive drag-and-drop environment

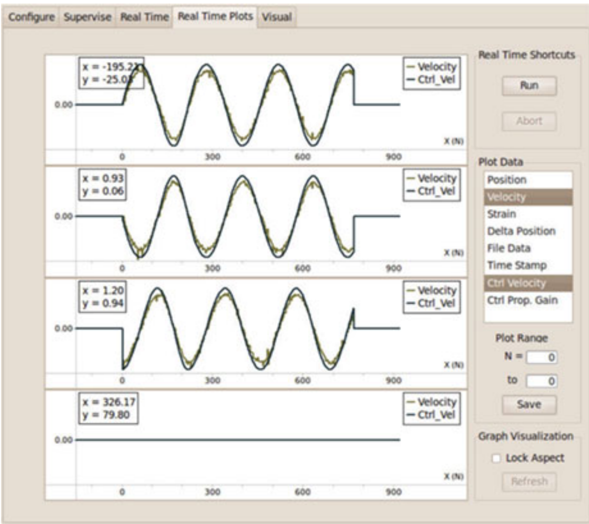


**Fig. 18** Integrated graphing/plotting functionality

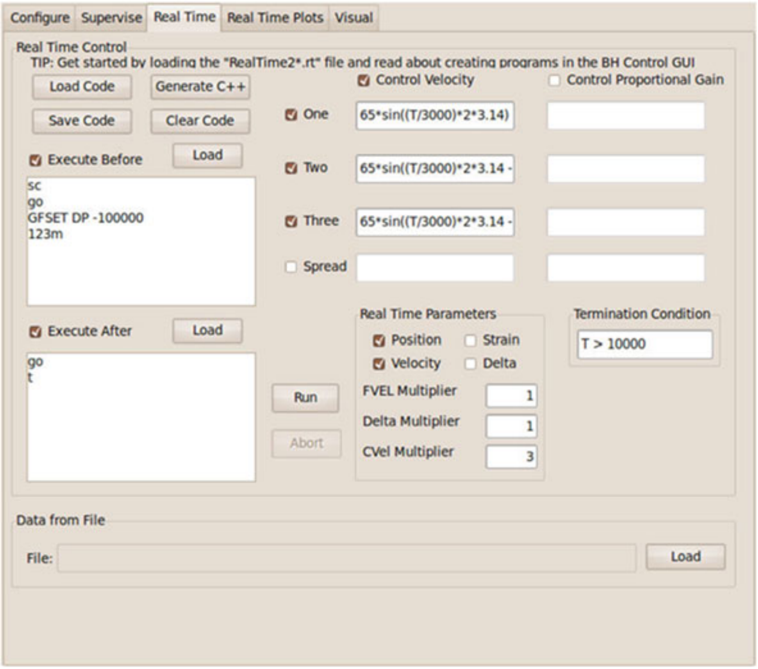


**Fig. 19** Realtime control, where more sophisticated control can be applied

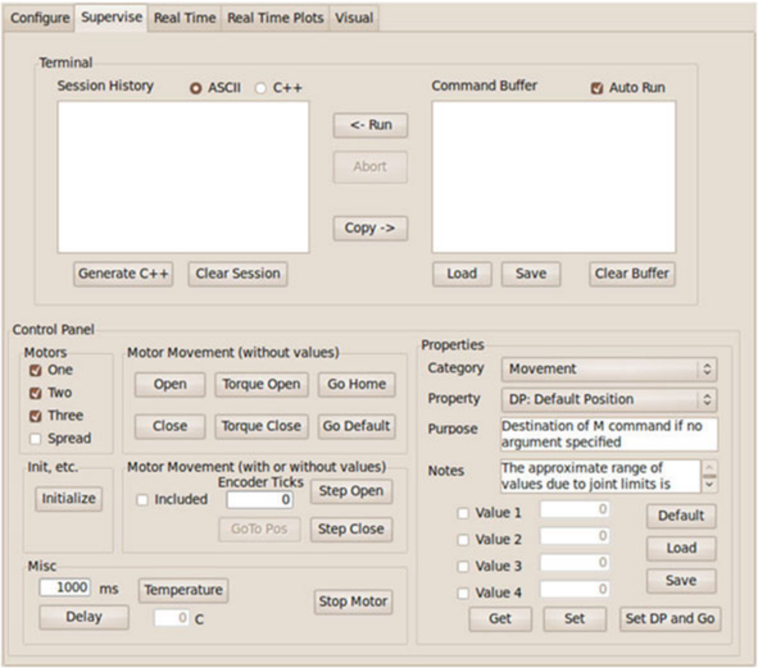


**Fig. 20** Supervisory control, where a series of commands can be used in sequence

that grasp during production. For more advanced grasping methods, including dynamic motion control based on real-time sensor feedback, the BarrettHand's full application programming interface (API) is published here: http://web.barrett.com/bhand/index.html.

It is important to recognize that graspers generally remain inactive during most of the workcell cycle, while the arm is performing its gross motions and, in nearly all cases, are only active for short bursts at the ends of an arm's trajectories.

While the robotic arm requires high control bandwidth during the entire cycle, the grasper has plenty of time to receive a large amount of setup information as it approaches its target. Then, with precision timing, the workcell controller releases a "trigger" command that begins grasp execution immediately.

## 6 Conclusion

Since the BarrettHand was introduced commercially in the early 1990s, nearly 400 units have been put into service around the globe at a single-unit price of US$29,500 and a large-order-quantity price of US$10,000. The largest concentration of graspers is among researchers studying advanced robotics around the globe. Many bodies of software have been written to control vision-guided grasping. For example, GraspIt was developed by Prof. Peter Allen at Columbia University to handle vision-guided decision making for grasping various geometries. This remains a challenging research topic, but once that software matures and becomes fully commercialized, graspers will quickly become common in manufacturing and service robotics. These manufacturers are only beginning to explore the capabilities of this versatile device.

The BarrettHand may have been invented before the surrounding technology was ready to embrace it fully. Before today, artificial intelligence and computational power have not been powerful enough to handle and exploit the rich sensor capabilities and dexterity of today's graspers in real time. However, we fully expect that to change in the next few years, at which point there will almost certainly be a transformative proliferation of robotic systems that fully exploit the benefits of graspers.