Reading Reports

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Contents

1 A Low-Cost Laser Distance Sensor

1.1 Reference

Konolige, K., Augenbraun, J., Donaldson, N., Fiebig, C., & Shah, P. (2008, May). A low-cost laser distance sensor. In Robotics and Automation, ICRA 2008. IEEE International Conference on (pp. 3002-3008).

1.2 Abstract

Many indoor robotics systems use laser range-finders as their primary sensor for mapping, localization, and obstacle avoidance. The cost and power of such systems is a major roadblock to the deployment of low-cost, efficient consumer robot platforms for home use. In this paper, we describe a compact, planar laser distance sensor (LDS) that has capabilities comparable to current laser scanners: 3 cm accuracy out to 6 m, 10 Hz acquisition, and 1 degree resolution over a full 360 degree scan. The build cost of this device, using COTS electronics and custom mechanical tooling, is under $30.

1.3 Summary

Konolige, et al. developed a low cost Laser Distance Sensor for mobile robot navigation. Since LDS are high cost, they are not used in consumer electronics. The main aim for this sensor it to be usable for consumer electronics like a vacuuming or delivery robot. The authors of the paper are using low cost components to build the LDS and compensate for inaccuracies with their approach.

They use point beam triangulation for distance measurements that works within a range of 0.2 m to 6 m. an advantage over other sensor is the 360 FOV achieved by rotation instead of mirrors. They use mechanical movement, approximation and a two step calibration process for module calibration.
Overall steps to provide distance readings involves:

1. Pulsing laser and exposing imager receiver.
2. Reading imager information.
3. Processing information to determine laser dot centroid.
4. Calculate distance to image centroid.
5. Output of distance measured.

1.4 Notes

- Claim their LDS capabilities are comparable to current laser scanners used in robotics.
- Has advantage over other sensors.
- Sensor has the following characteristics:
    1. Eye-safe
    2. Works under standard indoor lighting conditions, and some outdoor conditions.
    3. Measures a full 360 degree planar scan.
    4. Has a range from 0.2 m to 6 m.
    5. High resolution: range error ¡ 3 cm at 6 m, angular resolution of 1 degree.
    6. 4000 readings per second (scans up to 10 Hz)
    7. Small size, low power (¡ 2 W)
    8. Standard, commercially-available components.

9. Low cost: $30 cost to build.

- Mechanical compensation for laser pointing angle.
- Find best approximation for lens pointing angle.
- Two step calibration for lens distortion.
- Plan to find a way for better laser dot localization.
- Movement of chassis can cause high distortions.
- Does not work when staring directly to bright source of light.
- Small and rigid device.
- Low durability due to mechanical scanning.

1.5 Evaluation

Their approach accounts for many of the inaccuracies of building a sensor using low cost components. They manage to bring the cost down significantly and to a reasonable price for consumer electronics. Whether it is good enough for real application in a robot is unknown as it is just a proof of concept. A big factor of this can be attributed to the low durability of the sensor. For future work, I consider increasing durability a big improvement to work on.

2 Adaptive Kalman filtering for low-cost INS/GPS

2.1 Reference

Hide, C., Moore, T., & Smith, M. (2003). Adaptive Kalman filtering for low-cost INS/GPS. The Journal of Navigation, (Vol. 56, Issue 1, pp. 143-152).

2.2 Abstract

GPS and low-cost INS sensors are widely used for positioning and attitude determination applications. Low-cost inertial sensors exhibit large errors that can be compensated using position and velocity updates from GPS. Combining both sensors using a Kalman filter provides high-accuracy, real-time navigation. A conventional Kalman filter relies on the correct definition of the measurement and process noise matrices, which are generally defined a priori and remain fixed throughout the processing run. Adaptive Kalman filtering techniques use the residual sequences to adapt the stochastic properties of the filter on line to correspond to the temporal dependence of the errors involved. This paper examines the use of three adaptive filtering techniques. These are artificially scaling the predicted Kalman filter covariance, the Adaptive Kalman Filter and Multiple Model Adaptive Estimation. The algorithms are tested with the GPS and inertial data simulation software. A trajectory taken from a real marine trial is used to test the dynamic alignment of the inertial sensor errors. Results show that on line estimation of the stochastic properties of the inertial system can significantly improve the speed of the dynamic alignment and potentially improve the overall navigation accuracy and integrity.

2.3 Summary

There exist a wide variety of Inertial Motion Units(IMU), but they all come with errors that must be compensated. The main purpose of this paper is to find an adequate way of obtaining high-accuracy and real-time navigation using a low-cost INS sensor and a GPS and filtering the noise or error that the low-cost INS produces.

They study three different approaches for error filtering: Adaptive Kalman filtering, Kalman scaling with covariance matrix, and Multiple Model Adaptive Estimation.

KinPos, a software developed by IESSG, is used for processing measurements. It processes raw GPS and INS measurements using Kalman filtering. This software is capable of implementing the three methodologies of Kalman filtering previously mentioned.

For covariance scaling, they used four empirical factors to scale the covariance matrix.Testing for covariance scaling proved to be faster than conventional Kalman filtering.

Authors introduce an new process to estimate noise for adaptive Kalman filtering that improves stability and adaptability. It provides a self-tunning method for adapting the covariance matrix of the filter. This method produces a new estimate based on previous estimates. This method calculates precise estimates in approximately 100 seconds. Due to the recursive nature of the filer estimate, it need a prior initialization of an estimate, which means it is not entirely self tunning.

Multiple Model Adaptive Estimation runs eight parallel Kalman filters using different noise matrices. MMAE filtering approach was found to be ten times falter in filtering noise, but it comes at the cost of high computational load as it needs to run simultaneous processes.

2.4 Notes

- Adaptation to vehicle dynamics and environment conditions.

- Use of three approaches:
  1. Adaptive Karlman filtering.
  2. Kalman scaling with covariance matrix
  3. Multiple Model Adaptive Estimation
- Adapting for measured and processed noise.
- KinPos, software for processing measurements.
- Simulations to asses performance of algorithms.
- The disadvantages of the adaptive Kalman filter are primarily related to filter stability. (not entirely self-tuning)
- MMAE drawback is the computational load.

2.5 Evaluation

GPS and low-cost INS sensors are widely used for position estimation, but low-cost INS sensor produce many errors that need to be compensated. The authors of this paper present the result of three approaches for noise filtering in GPS and INS sensor readings. I consider that the different approaches may not apply for the same situations. For example, the MMAE approach results proved to be much faster in filtering noise and producing a smoother position estimation but at high computational cost. Since high computational capacity is required for this approach, I consider that this third approach should not be further studied if low-cost and efficiency is important.

3 An inexpensive robot platform for teleoperation and experimentation

3.1 Reference

Lazewatsky, D. A., & Smart, W. D. (2011, May). An inexpensive robot platform for teleoperation and experimentation. In Robotics and Automation, ICRA 2011. IEEE International Conference on (pp. 1211-1216).

3.2 Abstract

Most commercially-available robots are either aimed at the research community, or are designed with a single purpose in mind. The extensive hobbyist community has tended to focus on the hardware and the low-level software aspects. We claim that there is a need for a low-cost, general-purpose robot, accessible to the hobbyist community, with sufficient computation and sensing to run research-grade software. In this paper, we describe the design and implementation of such a robot. We explicitly outline our design goals, and show how a capable robot can be assembled from off-the-shelf parts, for a modest cost, by a single person with only a few tools. We also show how the robot can be used as a low-cost telepresence platform, giving the system a concrete purpose beyond being a low-cost development platform.

3.3 Summary

Lazewatsky and Smart present a robot made from consumer available products that can be used for telepréscence. The main goal of this paper is to allow for robotics hobbyists to be able to experiment with research-grade software built from off-the-shelf part so that it can be accessible and low cost. The proposed design of the mobile robot is using an iRobot Create as base, with a notebook clamped at a top of a stand extending from the base. At the top of the stand it contains 2 cameras used for navigation and the other one for teleoperation. Design goal for this system is to be easy to assemble, accessible to non-experts, low cost, made from off the shelf parts and to be capable.

Using off the shelf parts result in a number of limitations.

- Inaccurate Pan/Tilt movement: Since the camera is not able to report pose, it cannot be commanded to to a given pose. For this, An extended Kalman filter is implemented to model error in motor encoders and track current pose with the pan/tilt mechanism.
- Unstable, lightweight base: It has major stability issues due to the base being light compared to the overall weight of the robot. This was solved by imposing speed constraints to increase stability.
- No depth sensor: The robot does not include depth sensors, so they rely on a low resolution camera and implementing Horswill Polly algorithm for basic obstacle avoidance.

ROS is used for robot control software. They provide instructions to assemble their designed robot and an example telepresence application so that is can be used "out of the box". Necessary parts are made available in a list online, so it is easier for users to get the parts. Instructions for robot assembly are also available. Once hardware is assembled, user must install a version of Ubuntu and ROS packages. Once, OS and ROS middleware are in place, the telepresence application can be accessed by executing a script that will start the web interface, which can be accessed from other computers via web browser.

3.4 Notes

- Design goals:

1. Made from off the shelf parts
2. Easy to assemble
3. Low cost
4. Useful
5. Open and extensible
6. Accessible to non experts
7. Capable

- Costs approximately $998.12 USD as of Jan 2011
- Hardware used:
  1. Base: iRobot Create.
  2. Computer: Lenovo S10-3T netbook.
  3. Pan/Tilt camera: Logitech Orbit USB Camera.
  4. Navigation Camera: Logitech QuickCam Pro 9000.
  5. Body: 80/20 T-slotted extrusion.
- Assume users are competent enough to be capable of building their designed robot with manuals provided.
- Inaccurate pan/tilt movement of camera.
- Unstable
- No aditional sensors
- Potential users must buy part separately, assemble, install software by themselves.
- Use ROS for robot control
- Includes telepresence application.
- Future work includes developing a Linux distribution with necessary software preinstalled.

3.5 Evaluation

Authors present a design for a mobile robot to be used by robotics enthusiasts that do not want to invest in research level robots and is general enough to be able to test software in it. They manage to do it to some extent because the robot control is based on ROS, which makes it usable for many applications. The main disadvantage is that it has no distance sensors coupled, so it can not report exact position and can only avoid obstacles with a low resolution camera. The solution proposed for the stability issue does not fully solve it and rather just avoid it by imposing speed limits. The paper mentions they provide detailed and comprehensible instructions for assembly and installation of software. I consider this manuals to be very important in the desicion of using their proposed robot or not, because users may be swayed away if it is too complicated to build and make it run.

Even with these limitations, and while the authors' approach is far from optimal, I consider using of the shelf part to build a robot to be useful for experimenting and research. Not all researchers have sufficient resources to buy, so having instructions for building a working robot can help.

4 Design and analysis of a robust, low-cost, highly articulated manipulator enabled by jamming of granular media

4.1 Reference

Cheng, N. G., Lobovsky, M. B., Keating, S. J., Setapen, A. M., Gero, K. I., Hosoi, A. E., & Iagnemma, K. D. (2012, May). Design and analysis of a robust, low-cost, highly articulated manipulator enabled by jamming of granular media. In Robotics and Automation, ICRA 2012. IEEE International Conference on (pp. 4328-4333).

4.2 Abstract

Hyper-redundant manipulators can be fragile, expensive, and limited in their flexibility due to the distributed and bulky actuators that are typically used to achieve the precision and degrees of freedom (DOFs) required. Here, a manipulator is proposed that is robust, high-force, low-cost, and highly articulated without employing traditional actuators mounted at the manipulator joints. Rather, local tunable stiffness is coupled with off-board spooler motors and tension cables to achieve complex manipulator configurations. Tunable stiffness is achieved by reversible jamming of granular media, which-by applying a vacuum to enclosed grains-causes the grains to transition between solid-like states and liquid-like ones. Experimental studies were conducted to identify grains with high strength-to-weight performance. A prototype of the manipulator is presented with performance analysis, with emphasis on speed, strength, and articulation. This novel design for a manipulator-and use of jamming for robotic applications in general-could greatly benefit applications such as human-safe robotics and systems in which robots need to exhibit high flexibility to conform to their environments.

4.3 Summary

The main goal of this paper is to further understand the use and applications of jamming for robotics. Cheng et. al. present a robotic manipulator composed of granular modules connected in series that can transition between liquid state and solid state, effectively granting it flexibility and rigidness at the same time. It also allows to build human safe manipulators, because the manipulators are not bulky and the transitions between one position to another are done in the liquid like state of the media. Tension cables controlled by motors run along the manipulator eliminating the need for bulky motors in joints and allowing the manipulator to achieve complex configurations.

Jamming (effective solid phase) occurs when the density of particles exceeds a particular threshold, and this threshold is different for different materials. Physical properties of materials also affect friction, which can affect how quickly the media can transition between solid ans liquid like states.Four different materials were used as granular media: ground coffee, sawdust, diatomaceous earth, and hollow glass spheres. Ground coffee was used for prototypes as it showed better strength-to-weight ration under compression for stiffness. The differential jamming pressure for compression test for all media used was 75 kPa.

Two prototyped were built. The first prototype was composed of five identical segments of 50 mm length and an 8 mm diameter spring with stiffness 600 N/m was implemented in each segment. A Silicon membrane (1.5 mm thick) was cast outside to prevent membranes to buckle.This prototype exhibited high flexibility and could hold complex shapes, but barely enough strength to support its own weight. The second prototype was created with the primary goal of improve strength-to-weight performance and payload capacity of manipulator from that of the previous prototype. Prototype II had a thin latex sheet (150 microns thick) that replaced silicon membranes. This prototype was coupled with motors that controlled length of cables and valves for controlling air flow at each segment. A Vacuum pump with maximum of 101.3 kPa vacuum pressure was used to jam segments. It also included a vacuum storage tanks added to increase short-term volumetric flow rate of air.

Performance measure for their second prototype were speed, strength and dexterity. For their speed parameter, they measure only the time it takes for the manipulators to transition between jammed and unjammed states, with a result of 0.2s to jam - 0.1s to unjam. For strength, the load that the manipulators can support in their jammed states was used. It was found that it can support more than double of its weight as it could support 80g without tension cables - 740g with tension cables. (200g and 280g, weights of prototypes I and II respectively). The dexterity parameter was tested by verifying that the manipulator can achieve the same end position with multiple configurations and hold highly articulated configurations.

However, it has certain limitations and improvements it can be made. Since it lacks sensors, it can not determine shape and position. Strength of the manipulator can also be improved by integrating plumbing more seamlessly into the manipulator. Maximum differential vacuum pressure is atmospheric pressure, therefore, utilizing positive pressure can increase strength of jammed system. A rotational degree of freedom can also be added to the robot.

4.4 Notes

- Goal is further use and understanding of jamming for engineering applications.
- Local tunable stiffness is coupled with off-board spooler motors and tension cables to achieve complex manipulator configurations.
- Use of Jamming granular media to transition between solid and liquid like state.
- Allows more human safety and inexpensiveness.
- Grain properties affect the performance.
- Pneumatic, electromagnetic and hydraulic actuators have been used for similar applications.
- Need for mimic biological systems and maintain complex configurations.
- Jamming (effective solid phase) occurs when the density of particles exceeds a threshold.
- Different materials have different thresholds.
- Fast activation time for Jamming is needed.
- Friction of physical grain parameters affect flowing between transitions.
- For all compression tests the differential jamming pressure was 75 kPa.
- The materials tested were: ground coffee, sawdust, diatomaceous earth, and hollow glass spheres. (1050 microns diameter).
- Ground coffee was used for prototypes as it showed better strength-to-weight ration under compression for stiffness.
- Two prototypes designed.
  - Prototype I:
    * Composed of five identical segments of 50 mm length.
    * 8 mm diameter spring with stiffness 600 N/m was implemented in each segment.
    * Silicon membrane (1.5 mm thick) was cast outside to prevent membranes to buckle.
    * Prototype exhibited high flexibility and could hold complex shapes, but barely enough strength to support its own weight.
  - Prototype II:
    * Primary goal was to improve strength-to-weight performance and payload capacity of manipulator.

    * Thin latex sheets (150 microns thick) replaced silicon membranes.
    * This prototype was coupled with motors that controlled length of cables and valves for controlling air flow at each segment.
    * Vacuum pump wih maximum 101.3 kPa vacuum pressure was used to jam segments.
    * Vacuum storage tanks added to increase short-term volumetric flow rate of air.

- Performance parameters: speed, strength, dexterity and articulation with simple control.
- 0.2s to jam - 0.1s to unjam
- Support 80g without tension cables - 740g with tension cables. (200g and 280g, weights of prototypes)
- Can reach same end effector position with many configurations.
- Can maintain highly articulated configurations.
- Need sensors to determine shape and position.

4.5 Evaluation

Author present an innovative approach for manipulators, but it has many features that must be improved to be effectively used in real life applications. The choice for granular media, was to say the least, unexpected. To my consideration, more materials should have been tested to justify the need to build a prototype. As the authors mentioned, new problems for motion and path planning arise for this type of manipulators. So far, it is not possible to determine exact end effector positions as there is no sensor coupled to the manipulator.

While the authors' approach is far from optimal, I consider granular media to be an important topic for low cost robotics. It certainly caters to the low cost part, and the authors proved that their solution works. Granular media is certainly a topic that need to be researched more.

5 Design and implementation of a low cost 3D printed humanoid robotic platform

5.1 Reference

Cheng, H., & Ji, G. (2016, June). Design and implementation of a low cost 3D printed humanoid robotic platform. In Cyber Technology in Automation, Control, and Intelligent Systems, CYBER 2016. IEEE International Conference on (pp. 86-91).

5.2 Abstract

Humanoid robot with dual manipulators and dexterous hands shows great significance in domestic, medical and service applications. They can provide companion, operation, manipulation, material handling and many other services to human beings. However, current humanoid robots are either too expansive or too clumsy. There is a trade-off between robot flexibility and costs. It is a huge obstacle blocking the road of humanoid robot toward our daily life. In this paper, the design and implementation of a low cost dual wheel and dual arm humanoid robotic platform is introduced. The robot is based on the open source 3D printed humanoid robot InMoov. To fully explore the potential of InMoov, we redesigned its electrical system based on the developed Embedded Controller, and equipped it with a Mini PC and a touch screen for human-robot interaction. By using the 485 bus and modbus protocol, the wiring complexity is greatly decreased. A differential drive mobile platform is integrated to enable the robot with mobility and furthermore, a data glove system is also designed to explore a new type of robot programming technology. Robot Operating System(ROS) is used to realize the robot control and human-robot interaction. Comparing to the existing humanoid robots, the developed humanoid robotic platform is low cost but has fully functionality.

5.3 Summary

"It is ideal for the humanoid robots to bee similar with human appearances and functions as much as possible". Based on the previous quote from the authors, they designed and implemented a 3D printed humanoid robot (imNEU) based on InMoov. The robot system is divided in six submodules that are paired with an arduino controller to coordinate them, the modules are comprised of the head, torso, two arms, and two hands. Those six modules are completely 3D printed with Poliactid Acid, a biodegradable material. The robot is designed to be at an approximate height of a normal human (170 cm). Its cost is approximately 1600 dollars. Current imNEU is a nonholonomic and under-actuated mechanical system. Instead of legs, a two wheeled differential mobile platform is used for mobility as it enables more stability, control, and efficiency.

Mobile platform is made of aluminum plates and contains battery that powers all the modules. The processing ability comes from a mini PC mounted at the back of the torso, which can communicate with the Arduino controller through serial interface. The torso is connected to the arms by the shoulders, and each arm has 4 DOFs. Each arm is connected to a dexterous hand by a wrist joint module. Interaction with humans comes from a Kinect sensor for external sensing and a touch screen for feedback. It also contains data gloves that register pressure and touch were made for robot to be able to interact using its hands (Operator wears data glove and control dexterous hands to open and close them). Since components have different power requirements, means of power conversion, management and isolation is required.

Just as the robot is divided in modules, the software is also divided in four layer: the user layer, data processing layer, communication layer and executive layer. The user layer functions directly interacting with the robot operator, touch screen, data glove, wireless joypad, and Kinect sensor. Data processing layer consists of mini pc which gets commands from Kinect, data glove, and wireless joypad. The communication layer is in charge of communication between Arduino Mega 2560 and the six embedded modules. The execution layer consists of servo motors and the hub wheeled motors.

5.4 Notes

- ”It is ideal for the humanoid robots to bee similar with human appearances and functions as much as possible”.
- Based on InMoov open source 3D printed robot.
- Can be created with a 3D printer with 15x15x15cm space.
- Humanoid aspects contain: hands, arms, head and torso.
- Humanoid upper body is 3D printed.
- Mobility is enabled with a differential drive platform.
- ROS is used for control and human-robot interaction.
- Touchscreen and Kinect sensor added to torso.
- 170cm of height.
- Costs 1600 dollars.
- 47 DoFs, but with 25 motors.
- Battery pack located in mobile base.
- Mobile base made of aluminum plates, with a height of 60 cm.
- Robot has two configurations:
  - Two wheel differential driven mode.
  - Four wheel static balance mode.
- Mechanical and electrical parts are organized as modules.
- Used Poliactid Acid (biodegradable) for upper body.
- Left and right dexterous modular hands have five fingers and a wrist joint respectively.
- Left and right shoulder and elbow joint module are symmetric with 4 DOFs each.
- Processing comes from a mini PC with following specs: i3-5010U CPU, 4G memory, 128 GB SSD.
- Runs Ubuntu and ROS.
- Data gloves with pressure sensors to interact with dexterous hands. (Operator wears data glove and control dexterous hands to open and close them)
- Software modulated in layers:
  - User layer: functions directly interacting with the robot operator, touch screen, data glove, wireless joypad, and Kinect sensor.
  - Data processing layer: consists of mini pc which gets commands from Kinect, data glove, and wireless joypad.
  - Communication layer: Communication between Arduino Mega 2560 and six embedded modules.
  - Execution layer: Consists of servo motors and the hub wheeled motors.

5.5 Evaluation

Cheng et al. proposed an interesting design for a a humanoid robot which I consider that has a high potential to be used in human-robot interaction applications. Since a Kinect sensor, touchscreen and data gloves can be useful for human-robot interaction. I have two main concerns regarding this proposed robot. First, the effectiveness of the robot. Should the robot prove to be effective in real life use, then the actual cost of 1600 dollars can be considered low-cost. Second, how durable the robot is. Interaction with humans can be rough and uncertain for robot, so it would need withstand these rough interactions to be useful.

3D printing has been made widely available for just a couple years, and with its rapid growth and support it is getting, it is natural that 3D printing technology will be included in robotics, specially low cost robotics, because of all the applications it can have.

6 A low-cost compliant 7-DOF robotic manipulator

6.1 Reference

Quigley, M., Asbeck, A., & Ng, A. (2011, May). A low-cost compliant 7-DOF robotic manipulator. In Robotics and Automation, ICRA 2011. IEEE International Conference on (pp. 6051-6058).

6.2 Abstract

We present the design of a new low-cost series elastic robotic arm. The arm is unique in that it achieves reasonable performance for the envisioned tasks (backlash-free, sub-3mm repeatability, moves at 1.5m/s, 2kg payload) but with a significantly lower parts cost than comparable manipulators. The paper explores the design decisions and tradeoffs made in achieving this combination of price and performance. A new, human-safe design is also described: the arm uses stepper motors with a series-elastic transmission for the proximal four degrees of freedom (DOF), and non-series-elastic robotics servos for the distal three DOF. Tradeoffs of the design are discussed, especially in the areas of human safety and control bandwidth. The arm is used to demonstrate pancake cooking (pouring batter, flipping pancakes), using the intrinsic compliance of the arm to aid in interaction with objects.

6.3 Summary

The authors present a low custom design for a low-cost robotic arm for research. The main goal is to create robotic arm that is low cost ($4135 for this arm), human safe and can achieve high repeatability and payload without backlash. For their approach, they use stepper motors and a series of timing belts and cable circuits followed by series-elastic coupling for their overall design. It was designed to work at table high. Its shoulder has nearly 180 degrees of motion that allow it to reach the ground from its table height. Ros is used for system integration and visualization.
Many robotic arms exist today, but with features that are unique in design en for specific purposes, which come at high cost. For this robotic arm, a set of requirements where chosen to ensure the arm would be useful for manipulation research:

- Human-scale wokspace.
- 7 DOF.
- At least 2 kg of payload.
- Human safe:
  - Compliant or easily backdrivable.
  - Flying mass under 4 kg.
- Repeatability under 3 mm.
- Maximum speed of at least 1 m/s.
- Zero backlash.

Overall design consists of spherical shoulder and wrist connected by an elbow. The actuation scheme follows that joints are driven by stepper motors, with speed reduction by timing belts ad cable circuits, followed by a series-elastic coupling. To decrease bulk of arm, motors are located closer to the ground.

There are trade-offs for using stepper motors as actuators for the arm. Some advantages are that stepper motors are good at providing large torque at low speeds. It is also improving safety. For example, if a force is applied that exceeds its torque, the stepper motor will slip and the arm will move some distance until force is low enough that the arm can rearrange. Disadvantages include the need for re-calibration if the motor slips. Also, the arm may move suddenly due to a stepper motor slip if relatively large amount of force is applied.

Laser-cutting 5-ply plywood was used for most of the structure of the arm to reduce cost. Authors do not know how the arm will respond is are is subjected to an environment with high temperature and high humidity.

Performance was measured by testing repeatability by moving alternately between an initial position and eight distributed locations. Accuracy is within ± 1 mm. Payload was measured by adding weights until the stepper motor slipped, giving a payload of 2 kg. Maximum velocity was measured by observing end-effector velocity, giving a maximum velocity of 1.5 m/s.

6.4 Notes

- Focus on repeatability, low backlash, efficient payload and human-safety.
- Unit costs $4135
- Requirements:
  - Human-scale workspace.
  - 7 DOF.
  - At least 2 kg of payload.
  - Human safe:
    - Compliant or easily back-drivable.
    - Flying mass under 4 kg.
  - Repeatability under 3 mm.
  - Maximum speed of at least 1 m/s.
  - Zero backlash.
- Arm uses low-cost. stepper motors in conjunction with timing belt and cable. drives to achieve backlash-free performance.
- Motors placed close to ground (human safety).
- There are many robotic arms with unique features. (This arm does not bring anything new)
- Arm designed to be mounted at table height.
- It can reach floor and work at tabletop.
- Shoulder-lift joint has nearly 180 degree.
- Timing belts enable incremental motions (0.5 mm) and prevent gear damage under external force.
- Arm uses joint angle encoders for state estimation.
- Series-elastic actuators for proximal 4 DOF and non-sea for distal 3 DOF.
- One important trade-off with a series-elastic robot arm is the arm inertia and series elastic stiffness.
- Stepper motor cost $700.
- Structure may of 5-ply plywood.
- Unknown how will wood respond to large temperature and humidity variations.
- compliant coupling for proximal 4 joints.

- Joint angles are measured directly using optical encoders.
- In the future, initial static pose estimation will be provided by accelerometers.
- To simplify the manipulator wiring, the stepper-motor drivers and servos share a common RS-485 bus.
- Sensors are sampled and actuators are commanded at 100 Hertz.
- System integration and visualization is performed by ROS.
- Arm achieved properties:
  - Length: 1 m to wrist.
  - Total mass: 11.4 kg.
  - Moving mass: 2 kg.
  - Payload: 2 kg.
  - Max. speed: 1.5 m/s.
  - Repeatability 3 mm.
- Created a demonstration application of cooking pancakes.

6.5 Evaluation

The authors do not present an new approach for a robotic arm, instead, they bring another alternative to the many robotics arms in the market. Although there are many robotic arms, the low cost ($4135) to performance ratio makes it a good alternative as it showed that it can be used for real world application such as chess playing and pancake cooking. Since the robot arm is human safe, it can be used in applications involving human interaction.

The use of stepper motors can help in developing robot arms that are very cost effective with a respectable performance that can be used for research purposes and eventually to other real world applications like the one already mentioned.

7 Design and testing of a low-cost robotic wheel-chair prototype

7.1 Reference

Miller, D. P., & Slack, M. G. (1995). Design and testing of a low-cost robotic wheelchair prototype. Autonomous Robots, (Vol. 2, Issue 1, pp. 77-88).

7.2 Abstract

Many people who are mobility impaired are, for a variety of reasons, incapable of using an ordinary wheelchair. In some instances, a power wheelchair also cannot be used, usually because of the difficulty the person has in controlling it (often due to additional disabilities). This paper describes two low-cost robotic wheelchair prototypes that assist the operator of the chair in avoiding obstacles, going to pre-designated places, and maneuvering through doorways and other narrow or crowded areas. These systems can be interfaced to a variety of input devices, and can give the operator as much or as little moment by moment control of the chair as they wish. This paper describes both systems, the evolution from one system to another, and the lessons learned.

7.3 Summary

Miller et. al. bring two prototypes for a low cost robotic wheelchair. Their main purpose is to make a wheelchair for disabled people that needs little input in contrast to power wheelchair that need constant and accurate input from the user. Their solution contrasts from power wheelchairs, which are traditionally used by people who do not have upper body strength and dexterity to operate a manual wheelchair. However, operation of power wheelchair can still be difficult for some individuals with certain disabilities. The authors solution use a variety of sensors and microprocessor to aid the user in the operation of the wheelchair.
Two prototypes were created (Tin Man); both prototypes are built on a commercial wheelchair (Vector Wheelchair Corporation). The first design has no electrical interface for the robots computer, instead it uses servomotors to control the joystick that comes with the chair. There is an array of different sensor located at the base of the wheelchair that serve for basic task such as obstacle avoidance and wall-following. By default, the Tin Man I can run in three semi-automatic modes: human guided with obstacle avoidance, move forward along a heading, and move to x,y position. In all three modes, it follows the same priority scheme:

1. If contact sensor reads true, chair moves aways from point of contact.
2. If proximity sensor reads true and, then it will move aways in from direction of the sensor read.
3. If sonar senses obstacle < 60 cm away, then it will stop moving.
4. Robot moves in designated direction unless it conflicts with one of the previous points.
5. Chair will follow command from user input, unless it conflicts with one of the previous rules.

The second prototype includes an electrical interface for the robot control. It decreases reliance on contact sensor and increased operating speed. It has the same three basic modes plus and additional: turn avoiding obstacles. In this mode, it can turn both clockwise or anti-clockwise. The priority scheme is the same as the first prototype.

Tin Man II was tested extensively in office environment. Decoration consisted in dark wood, metallic gold trim and Plexiglas walled walkways. The result was positive, as it could handle most doorways. Experience did point out some limitations, such as when trying to go through an elevator door. The sensor would detect the back of elevator within certain distance so it would stop moving and needed to be switched to manual mode.

7.4 Notes

- Designed for people who cannot issue continuous and accurate input to a wheelchair.
- Two prototypes:
  - Tin man I:
    - Built on top of a commercial wheelchair. (Vector Wheelchair Corp)
    - No electrical interface between chair control and robots computer. (mechanical interface)
    - Control computer controls two servo motors that are mechanically linked to the standard joystick that comes with the chair.
    - Sensors:
      - Drive motor encoders
      - Contact sensors
      - IR proximity sensor
      - Sonar range finders
      - Fluxgate compass
    - Written in IC
    - Three semi automatic modes:
      1. Human guided with obstacle override.
      2. Move forward along a heading
      3. Move to X, Y.
    - Priority scheme:
      1. If contact sensor reads true, chair moves away.
      2. If proximity sensor reads true, chair will turn away.
      3. If sonar senses obstable ¡60cm, chair will not move.
      4. Robot follow designated heading unless conflict with 3 previous rules.
      5. Chair follows commands from user unless it conflicts with previous rules.
    - move to X, Y is meant to be used for mostly clear paths.
    - Test showed behavior governed mostly by sonars.
  - Tin man II:
    - Decreased reliance on contact sensors
    - modified user interface
    - Increased operating speed.
    - Also built on top of Vector Wheelchair Corp.
    - New digital to analog converters, we were able to electrically interface the microcontroller to the chair's wheelchair controller.
    - reduce dependence of contact sensor by adding twelve IR proximity sensors.
    - The chair can be made to navigate through doors and around most obstacles relying solely on the IR sensors.
    - Operates in four modes:
      - Human guided with obstacle override
      - Turn avoiding obstacles
      - Move forward avoiding obstacles
      - Manual mode
- Needs a way to dynamically set and store different bias sets for the various sensors.

7.5 Evaluation

The authors bring up a very important point/problem that can be solved with a robotic wheelchairs. Their first prototype is not a good solution, because it relies to much on contact sensors, which means it constantly bumps into objects. The second prototype solves this problem but there still are many scenarios that need to be improved. IR sensors will not work for every type of surface, so they need to come up with a solution for that before commercializing the wheelchair.

Even though this paper is more than 20 years old, I still consider that it is an important topic for low-cost robotics. Even today, there are very few commercially available wheelchairs that are truly autonomous or "smart". There needs to be a significant advance in sensor technology that can solve the problem of having low cost sensors and their accuracy.

8 Fast and inexpensive color image segmentation for interactive robots

8.1 Reference

Bruce, J., Balch, T., & Veloso, M. (2000). Fast and inexpensive color image segmentation for interactive robots. In Intelligent Robots and Systems, IROS 2000. IEEE/RSJ International Conference on (Vol. 3, pp. 2061-2066).

8.2 Abstract

Vision systems employing region segmentation by color are crucial in real-time mobile robot applications. With careful attention to algorithm efficiency, fast color image segmentation can be accomplished using commodity image capture and CPU hardware. This paper describes a system capable of tracking several hundred regions of up to 32 colors at 30 Hz on general purpose commodity hardware. The software system consists of: a novel implementation of a threshold classifier, a merging system to form regions through connected components, a separation and sorting system that gathers various region features, and a top down merging heuristic to approximate perceptual grouping. A key to the efficiency of our approach is a new method for accomplishing color space thresholding that enables a pixel to be classified into one or more, up to 32 colors, using only two logical AND operations. The algorithms and representations are described, as well as descriptions of three applications in which it has been used.

8.3 Summary

Bruce et. al. bring anew approach for and efficient low level color segmentation which can be applied in real time robot mobile applications. the overall approach consist of using thresholds in a three dimensional color space. They chose YUV color space, as hardware worked in this specific color space.

In their thresholding method, each color class is specified as a set of six threshold values: two for each dimension in the color space. To check if a pixel belongs to a particular color, they use boolean valued decomposition. It is significantly faster than integer compare on most modern processors. Also, rather than build a separate set of bit arrays for each color, they combined the arrays using each bit position an array element to represent the corresponding values for each color.

The next step involve grouping similar adjacent pixels as a single run, to avoid running same computation for similar pixels. Regions are labeled into a table for faster lookup. Before passing data, a merging heuristic is applied to help eliminate some error in region generation.

Their overall process consists of six steps:
First they project to YUV color space directly from hardware. Second, they classify each pixel region into one of 32 colors that using arrays for two bit-wise comparison operations. Third step involves using run length encode for each scanline according to color. Fourth step groups same color pixels into regions. Then, pass the information available using radix sort. Last step is completed in a single pass over the resulting data structure.

Results showed that system was able to track a ball moving at 4 m/s at a resolution of 640x480 using a 700MHz Pentium III processor.

8.4 Notes

- System capable of tracking several hundred regions of up to 32 colors at 30 Hertz on general purpose commodity hardware.
- Four main parts:
  1. Novel implementation of a threshold classifier.

2. A merging system to form regions through connected components.
3. A separation and sorting system that gathers various region features.
4. A top down merging heuristic to approximate perceptual grouping.

- Use YUV color space.
- Based on Boolean valued decomposition of multidimensional threshold.
- Can determine a pixel membership in multiple color classes simultaneously.
- Merging procedure:
  1. Compute run length encoded version for classified image.
  2. Tree-based union find with path compression.
- Next step is to extract information from merged RLE map.
  - Algorithm is passing over the image a run at a time.
  - The regions are separated based on color into separate threaded linked lists in the region table.
- Overall system operates in six steps:
  1. Optionally project the color space.
  2. Classify each pixel as one of up to 32 colors.
  3. Run length encode each scanline according to color.
  4. Group runs of the same color into regions.
  5. Pass over the structure gathering region statistics.
  6. Sort regions by color and size.

8.5 Evaluation

This is a very good approach for very basic/low-level object recognition using color classification. This algorithm can be useful in controlled environments where lightning conditions do not change much. There is a very crucial drawback in that pixel classification is done with an AND condition, and small variations in color can result in classification into the same color type, resulting in loss of information or wrong classification.

I consider it helps low cost robotics because in general, developing methods to make processing and classification of data more efficient helps devices with low processing power or systems that need a fast response. Particularly, for applications that need color segmentation, this approach decreases response time and leaves more resources for other processes.

9 Flexible force control for accurate low-cost robot drilling

9.1 Reference

Olsson, T., Robertsson, A., & Johansson, R. (2007, April). Flexible force control for accurate low-cost robot drilling. In Robotics and Automation, ICRA 2007. IEEE International Conference on (pp. 4770-4775).

9.2 Abstract

The problem of robot drilling presents a significant challenge, due to the comparatively low mechanical stiffness of typical serial industrial robots. This compliance makes the robot deflect due to the cutting forces, resulting in poor hole quality. Recently, functionality for high-bandwidth force control has found its way into industrial robot control systems. This could potentially open up the possibility of robotic drilling systems with improved performance, using only standard systems without costly extra hardware and calibration techniques. In this paper, we present methods and systems for force-controlled robot drilling, based on active suppression of drill sliding through a model-based force control scheme. The methods are validated in a number of drilling experiments using an industrial robot.

9.3 Summary

Olsson et. al. bring an approach that opens the possibility of improving the performance of industrial robot drilling using only a system based on force control scheme without the need of including costly hardware or additional calibration techniques. The setup consist of a robot holding a pneumatic drilling tool equipped with a pressure foot in the form of a tripod. Their solution is based on controlling the force applied by the robot arm using sensors mounted between drilling machine and the tripod that holds it.

The goal is to a constant normal force to the drilled surface with the tripod to keep the tangential force small enough so that it does not slides while drilling. To avoid sliding due to the deformation or bending of the robot, they use a model based inner loop compensation to improve "stiffness".

Authors compared results of drilling experiments with and without force control. For the first set of experiments using the built in motion control of the robot, the result was not satisfactory, as it showed deflection of 1.6 mm. Position and quality of holes resulted unsatisfactory. For the next set of experiments, they used their proposed method, which resulted in reducing deflection to 0.1 mm. The experiments indicate an increase in holes quality and position by reducing vibrations and increasing stiffness of the drilling tool.

9.4 Notes

- Systems for force-controlled robot drilling, based on active suppression of drill sliding through a model-based force control scheme.
- Setup consist of robot arm holding a drilling tool equipped with pressure foot in form of a tripod.
- Goal is to apply a constant normal force to the drilled surface and keep the tangential forces small enough to avoid sliding.
- Forces are measured using a stiff six-axis force/torque sensor mounted between the drilling machine and the tripod.
- Two step tunning:
  - Algorithm for static calibration was used to find the stiffness matrix.

  - Dynamic model was tuned given motion references and external tool forces as inputs.
  - Second order ODE used to emulate mass-spring-damper system.

- Inner motion control includes external force compensation to increase ”stiffness”.

- High-frequency disturbances are damped out by the tripod high-friction contact.

9.5 Evaluation

The paper focuses a lot on explaining the equations for their model, which is not necessarily good if there are reader that do not know many of the assumptions and implication made in the paper. But evidently, this approach can help industrial drilling with robotic arms because it focuses increasing the performance without the use of expensive additional hardware.

10 GPS-less low-cost outdoor localization for very small devices

10.1 Reference

Bulusu, N., Heidemann, J., & Estrin, D. (2000). GPS-less low-cost outdoor localization for very small devices. IEEE Personal Communications, 7(5), (28-34).

10.2 Abstract

Instrumenting the physical world through large networks of wireless sensor nodes, particularly for applications like environmental monitoring of water and soil, requires that these nodes be very small, lightweight, untethered, and unobtrusive. The problem of localization, that is, determining where a given node is physically located in a network, is a challenging one, and yet extremely crucial for many of these applications. Practical considerations such as the small size, form factor, cost and power constraints of nodes preclude the reliance on GPS of all nodes in these networks. We review localization techniques and evaluate the effectiveness of a very simple connectivity metric method for localization in outdoor environments that makes use of the inherent RF communications capabilities of these devices. A fixed number of reference points in the network with overlapping regions of coverage transmit periodic beacon signals. Nodes use a simple connectivity metric, which is more robust to environmental vagaries, to infer proximity to a given subset of these reference points. Nodes localize themselves to the centroid of their proximate reference points. The accuracy of localization is then dependent on the separation distance between two-adjacent reference points and the transmission range of these reference points. Initial experimental results show that the accuracy for 90 percent of our data points is within one-third of the separation distance. However, future work is needed to extend the technique to more cluttered environments.

10.3 Summary

Author of this paper focus on the localization of devices that are too small to contain a GPS. As such, their approach focuses on IR signal technology. Author talk about related approaches that can be classified into two groups:

- Fine grained localization
- Coarse grained localization

Their approach falls into the category of coarse grained localization, since localization is calculated based on known reference points. The main design goals the authors want to address in are:

- To be RF-based: eliminating cost, power and size of GPS receiver.
- Receiver based: responsibility of localization must lie within receiver node, and not by reference points.
- Ad hoc: does not require extensive planning.
- Responsiveness: low response time.
- Low energy: Minimize computation to reduce power consumption.
- Adaptive fidelity: accuracy to adapt depending of available reference points.

The paper discuses several range finding approaches that use fine grained localization: timing based, signal strength, signal pattern matching, and directionality. For coarse grained localization, they considered two approaches: signal strength and connectivity based approach. At the end, authors discarded signal strength based approach due to the short-range of radios used (10 m). To localize devices, multiple node in a network with overlapping regions of coverage serve as reference points. Signals are sent from these reference points and receivers infer position with proximity to a collection of several reference points. Since their approach must assume that radio signal propagates in a perfect sphere, their approach only works for outdoor environment, as wall and obstacles inside an indoor environment affects radio propagation.

The testing results in a 10 m x 10 m grid showed an average localization error of 1.83 m and the standard deviation was 1.07 m. The minimum error was 0 m and the maximum error was 4.12 m across 121 grid points.

Future work ideas include:

- Collision avoidance: they would need to synchronize beacon signal transmission.
- Tuning for energy conservation.
- Non-uniform reference point placement: in practice, reference points will not be evenly distributed.
- Robustness: should tolerate reference point failures.
- Adaptive to noisy environments: perfect spherical radio propagation does not hold in noisy environments.

10.4 Notes

- Based on radio frequency communications.
- Focus on small, light and unobtrusive devices.
- Applied to large sensor network systems for biological or environmental monitoring.
- Goals:
  - RF-based: eliminating cost, power and size requirements of GPS.
  - Receiver based: Localization must lie with the receiver node that needs to be localized.
  - Ad hoc: so that it does not require pre-planning or extensive infrastructure.
  - Low energy: minimize computation and message cost to reduce power consumption.
  - Adaptive fidelity: adaptive to the available reference points.
- Related work:
  - Fine-grained localization.
    - Time of flight
    - Signal strength
    - Signal pattern matching
    - Directionality
  - Coarse grained localization.
    - Active Badge
    - Optical sensing of IR beacons.
- Author's two approaches based on signal strength and connectivity respectively.
- Signal strength discarded due to short range radios used.
- Signal strength at short distances is unpredictable.
- Idealized Radio Model (based on connectivity)
  - Two assumptions:
    - Perfect spherical radio propagation

    * Identical transmission range for all radios.
  - Beacon signal transmitted by known reference points.
  - Each mobile node listens for fixed time to collect beacon signals.
  - The receiver localizes itself to the region which coincides to the intersection of the connectivity regions of this set of reference points.

- Error never ¿ 2m.
- No dead spots were observed.
- Not appropriate for indoor environments.

10.5 Evaluation

The tests made for this approach we only used in a 10 x 10 grid, so I consider it is very small range. Error was reported to be always less than 2 meters, but for a 10 m x 10 m grid it is a very high error margin. Even with this high error margin, this approach could be useful to low cost robotics if implementation can be extended to large scale systems in environmental sensing where position needs not to be exact.
Another drawback of this approach is that it can only be used outdoors, since walls can affect beacon signals and produce higher error in position estimation.

11 Human gesture recognition using a low cost stereo vision in rehab activities

11.1 Reference

Ismail, S. J., Rahman, M. A. A., Mazlan, S. A., & Zamzuri, H. (2015, October). Human gesture recognition using a low cost stereo vision in rehab activities. In Robotics and Intelligent Sensors, IRIS 2015.IEEE International Symposium on (pp. 220-225).

11.2 Abstract

During rehabilitation, patients tend to do several abnormal gestures to indicate their conditions. Since danger might happen to patients, especially without the supervision of therapist, a monitoring system should be developed. In this paper, a preliminary work is conducted to provide an online monitoring system to replace the therapist role to automatically monitor patient during the physical therapy activities by using a stepper. However, the main objective of this paper is to propose methods that can improve recognition rate of human gesture by implying Linear Discriminant Analysis (LDA) on features and then propose Support Vector Machine (SVM) as classifier. In order to accurately identify gesture of patients such as falling down during physical activities, angle features calculated from the information of head and torso positions is proposed as input data. A low cost RGB and depth camera will be used to track and capture the skeleton joint position of the patient. LDA of joint angles is proposed as feature in this research. The feature extracted will be analysed and classified using SVM to recognize the type of gestures performed by the patient during rehabilitation. As any abnormal gesture was recognized, the system will provide information to be used as an alarm for further supervision by the therapist.

11.3 Summary

When patient undergo a rehabilitation process, they need to have a therapist that helps and guides the patient according to its condition. The therapist usually acts as the supervisor and monitors the progress of the patient. authors in this paper, propose a system that is able to replace the need of a therapist to monitor the condition of the patient using a low cost stereo vision camera to recognize gestures such as falling down, calling for help, tired etc.

Their approach uses a low cost camera, and a software that will provide depth and skeleton information to keep track of 15 joints in the body. These joints include head, torso, neck, and left and right shoulders, elbows, wrists, hip, knee, and foot. The camera is able to capture 640x480 pixel resolution at 30 fps or 320x240 pixel at 60 fps.

The general process for gesture recognition starts with data acquisition. The camera is placed in front of the patient at a distance between 0.8 and 3.5m. The background of the image is removed so it reduces noise in image. There is a pre-processing step to remove remaining noise and normalize features to ensure a better recognition rate. As patient moves, head joint of patient will change. The change of position from torso in position 1 to head in position 1 to torso in position 1 to head in position n creates an angle which is used to calculate distance between joints. In order to have more robust features, LDA will be applied to joint angles. Based on other papers, authors predict a high recognition rate after LDA is applied.

They intend to use SVM as a classifier to classify gestures performed by the patient during rehabilitation. This algorithm is proficient in splitting data into two classes.

11.4 Notes

- Aim to provide a system that is capable of monitoring patients during rehabilitation using steppers, replacing the need for a therapist.

- Implement Linear Discriminant Analysis (LDA) on joint angle features and Support Vehicle Machine (SVM) as clasifier.
- Identify gestures such as: normal, falling down, calling for help, tired, etc.
- Focus on fall gestures.
- Selection of LDA of joint angles feature lead to a better recognition rate.
- Once features have been extracted, classification is needed.
- Asus Xtion Pro Live for low cost RGB and depth camera.
- Software: Open Natural Interaction Software Development Kit. (OpenNI SDK)
- Camera can capture 640x480 pixel at 30fps or 320x240 pixel at 60 fps.
- 15 joints include: head, neck, torso, and both left and right of shoulder, elbow, wrist, hip, knee, and foot.
- Experiment focus on only one patient.
  - Camera placed in front of patient between 0.8 and 3.5m. (tracking whole body)
  - Depth images and joint position information is recorded and saved in CVS format.
  - Pre-processing consist of noise removal, and pattern normalization.
  - Only X and Y coordinates are considered. Z is ignored.
  - As patient moves, head joint of patient will change.
  - The change of position from torso in position 1 to head in position 1 to torso in position 1 to head in position n creates an angle which is used to calculate distance between joints.

11.5 Evaluation

A very important problem is being addressed in this paper. Authors want to help therapists for patients undergoing rehabilitation. The main problem with this papers is that its proposed system is not implemented nor tested. Authors expect a high rate of gesture recognition out of their system, but it is not specified what model are they going to use to provide help or useful information for therapist.

12 Real-time Localization in Outdoor Environments Using Stereo Vision and Inexpensive GPS

12.1 Reference

Agrawal, M., & Konolige, K. (2006, August). Real-time Localization in Outdoor Environments Using Stereo Vision and Inexpensive GPS. In Pattern Recognition, ICPR 2006. IEEE International Conference on (Vol. 3, pp. 1063-1068).

12.2 Abstract

We describe a real-time, low-cost system to localize a mobile robot in outdoor environments. Our system relies on stereo vision to robustly estimate frame-to-frame motion in real time (also known as visual odometry). The motion estimation problem is formulated efficiently in the disparity space and results in accurate and robust estimates of the motion even for a small-baseline configuration. Our system uses inertial measurements to fill in motion estimates when visual odometry fails. This incremental motion is then fused with a low-cost GPS sensor using a Kalman filter to prevent long-term drifts. Experimental results are presented for outdoor localization in moderately sized environments (ges100 meters).

12.3 Summary

Authors of this paper present a low cost stereo vision system used for outdoor environment localization. They chose to use stereo vision because it is light-weight, compact, relatively inexpensive and can provide high resolution images at high frequency. Sonars and Laser range finders can also be used for outdoor localization but sonars are not very accurate, while Laser range are slow and bulky.

The setup of the robot consists of two stereo cameras located at the mast of a robot at 0.5 m above ground. These cameras have 100 degrees of FOV. These combined characteristics makes it difficult to accurately track points over large distances. Applying their stereo vision system overcomes this problem. The robot also uses two wheel encoders located on differential drive wheels, an IMU located on mast and a low cost GPS placed on top of mast. Standard plane based calibration is used for stereo cameras.

The visual odometry system use features to estimate motion between two frames coming from different cameras. A minimum of three features are needed to for correct estimation of pose. These features need to be spaced out or it will result in bad estimates. It is necessary to triangulate points to obtain 3D location an use SVD to obtain orientation. If there is an error less than 1.25 pixels then the features match. An image is given a score according to the number of matches. Then the Best score is used as starting point for Levenberg-Marquardt algorithm for nonlinear least squares minimization.

Since position is calculated from frames of a video, there will be drifting if robot is stationary. To solve this, reference frame is updated to avoid drifting. The coupled GPS provides measurement information for Kalman filter to correct pose estimates. Position information is used when receiver is stationary. Velocity information is used when moving.

The system was tested running closed loops of 50 to 100 m. GPS correct pose estimation for closed loop error. The visual odometry pose is correct and localizes robot well.

12.4 Notes

- Low cost robot localization for outdoor environments.
- SLAM very successful for indoor structured indoor environments.

- Current outdoor localization need expensive and high quality devices.
- SLAM can use sonars, laser range finders and vision.
- Sonar is fast and cheap but not very accurate.
- Laser range is accurate but slow and bulky.
- Vision systems are light-weight, compact, relatively inexpensive and can provide high resolution images at high frequency.
- Setup:
  - Bumbleblee stereo cameras are located on robot mast looking outward.
    * 100 degrees FOV, situated at 0.5m above ground, which makes it difficult to track points over large distance.
  - Two wheel encoders
  - Xsens IMU
  - Garmin GPS (<200$)
- System overview:
  - Visual Odometry:
    * Use of features to estimate motion between two frames.
    * Three features needed for estimation.
  - Initial pose obtained from IMU, wheel encoders and GPS by moving robot.
  - Kalman filter to prevent GPD long term drift.
- Related work (motion estimation):
  - Dense optical flow or sparse feature tracks.
  - Optical flow and planar world assumption.
  - Optical flow for stereo images.
  - Feature based approach using Harris corners or SIFT features.
- Visual odometry system:
  - Harris corners are detected between images of frames and matched.
  - Three features must be spaced out in the image.
  - Close features result in bad estimates.
  - Triangulate points to obtain 3D location an use SVD to obtain orientation.
  - Error within 1.25 pixels is a match.
  - Number of matches = score.
  - Best score is used as starting point for Levenberg-Marquardt algorithm for nonlinear least squares minimization.
  - Drift if robot is stationary.
  - Update reference frame to avoid drift.
  - Plane based calibration for stereo cameras.
- VO - accurate position but uncertain error in long term.
- GPS - readily available with certain error, but small jumps on short term.
- Kalman filter to fuse GPS:

  - GPS provides measurements for Kalman filter to correct pose estimates.
  - Position information is used when receiver is stationary.
  - Velocity information is used when moving.

- Robot tested running closed loops of 50-100m.
- Closed loop error corrected by GPS.
- Visual odometry pose is correct and localizes robot well.

12.5 Evaluation

The visual odometry approach presented by the authors work well and correctly estimates the pose to a certain degree of error. I consider this paper important for low cost robotics because current high quality sensor used for localization that provide accurate pose estimates are very costly. Authors contribute to the field of localization in outdoor environments with an approach that uses low cost, but effective hardware for localization.

13 Low cost indoor positioning system

13.1 Reference

Randell, C., & Muller, H. (2001, September). Low cost indoor positioning system. In International Conference on Ubiquitous Computing (pp. 42-48). Springer Berlin Heidelberg.

13.2 Abstract

This report describes a low cost indoor position sensing system utilising a combination of radio frequency and ultrasonics. Using a single rf transmitter and four ceiling mounted ultrasonic transmitters it provides coverage in a typical room in an area greater than 8m by 8m. As well as finding position within a room, it uses data encoded into the rf signal to determine the relevant web server for a building, and which floor and room the user is in.I t is intended to be used primarily by wearable/mobile computers, though it has also been extended for use as a tracking system.

13.3 Summary

Authors of this paper present an approach for position estimation in indoor environments using a low cost RF and ultrasonic transmitters. They use a single RF transmitter and four ultrasonic transmitters mounted in the ceiling of a room. Just as a GPS can locate a device in a 1 km x 1 km city within 15 m, authors want to locate a device in a 10 m x 10 m room within 15 cm.

To determine 3D position in a room, they require three distance measurements. The measurements are calculated based on time of flight of the ultrasonic signals. The RF signal is used for synchronization. Since only, three measurements are needed, the extra signal compensates for signal loss and to increase range of system.

The four ultrasonic transmitters are mounted facing downwards and is connected to a transmitter module containing the microcontroller and the rf transmitter. A receiver is mounted on a small module that can be attached to a mobile device or carried by the user.

Techniques used to increase effectiveness of system:

- Best Signal Selection: good signals are averaged.
- Non-Incident Angle Compensation: compensation for non-incident reception.
- Threshold Filtering: Eliminate position jitter by adding threshold.
- Speed Limit: only consider movement of max 1 m/s.
- 2D Estimation: when only two path can be measured, waist height is assumed for z coordinate.
- Averaging: final readings averaged with previous reading.

Tests showed a maximum error of 10 cm in a 4.2 x 6.5 m test room. Problems arise in environments with high ultrasonic noise.

13.4 Notes

- Low cost RF and ultrasonic transmitter.
- Commercial systems are expensive. (>$15,000)
- suitable for research applications

- Locate device within 15cm in 10x10m room.
- Use one rf signal as ping
- Four timed ultrasonic signals ad chirps to allow for "time of flight".
- Time of flight is converted into distance.
- Four chirps to increase range and to compensate for lost signal.
- Ping ensures receiver is synchronized with transmitter.
- Ping max range = 100m
- Chirps are transmitted at 50ms intervals.
- Ultrasonic transmitters are mounted on corners, facing downwards.
  - Connected to microcontroller and rf transmitter.
- Receiver is mounted in a small module that is attached to a device.
- Max tested error is of 10 cm.
- System may fail in environment with high ultrasonic noise.
- Primary techniques:
  - Best Signal Selection
  - Non-Incident Angle Compensation
  - Threshold Filtering
  - Speed Limit
  - 2D Estimation
  - Averaging
- Low price tag.
- Simple to install.
- Requires no calibration after initial installation.

13.5 Evaluation

Although the authors approach for indoor localization works, they did not test the system in a room of 10 m x 10 m as initially proposed. Since they are testing in a room that is a fourth of the expected size, result may be vary significantly. Another disadvantage of their approach, is that the receiver module may be bulky depending of the application. Also, the duration of the battery can only last one day until battery need to be replaced. Increasing duration and decreasing bulkyness should be important.

14 Low-cost dual rotating infrared sensor for mobile robot swarm applications

14.1 Reference

Lee, G., & Chong, N. Y. (2011). Low-cost dual rotating infrared sensor for mobile robot swarm applications. Industrial Informatics, 2011. IEEE Transactions on, (277-286.)

14.2 Abstract

This paper presents a novel low-cost position detection prototype from practical design to implementation of its control schemes. This prototype is designed to provide mobile robot swarms with advanced sensing capabilities in an efficient, cost-effective way. From the observation of bats' foraging behaviors, the prototype with a particular emphasis on variable rotation range and speed, as well as 360 degree observation capability has been developed. The prototype also aims at giving each robot reliable information about identification of neighboring robots from objects and their positions. For this purpose, an observation algorithm-based sensor is proposed. The implementation details are explained, and the effectiveness of the control schemes is verified through extensive experiments. The sensor provides real-time location of stationary targets positioned 100 cm away within an average error of 2.6 cm. Moreover, experimental results show that the prototype observation capability can be quite satisfactory for practical use of mobile robot swarms.

14.3 Summary

Authors of this paper propose an infrared sensor with a 360 degree field of vision to mimic bat-like sensing system with a dual rotating configuration. Their proposed sensor costs approximately 50 USD to built. For testing, they compare their sensor with a Hokuyo Ltd.'s URG-04LX laser sensor.

The main purpose of the paper is to build a prototype of dual rotating infrared (DRIr) sensor for a robot swarm, enable operating functions to control DRIr sensor motion and an observation algorithm to estimate position of other robots. Design goals for sensor include: low cost, compact, easy integration.

The sensor consists of two servo motors and an infrared sensor. The infrared sensor is attached to one of the motors that can rotate 180 degrees and this motor is attached to another motor which give it an additional 180 degrees of rotation. Authors built a custom mobile robot to test their sensors, which consists of a mobile robot base (MobileRobots Pioneer 3-DX) equipped with two DRIr sensors and a laptop as controller. The custom mobile robot is not able to properly use the 360 degree FOV from the sensor because the robot obstructs part of the view. They use two sensors to placed on the front and back to solve this. For each sensor, the base motor rotates 180 degrees (from -90 to 90) and the upper motor give and additional 60 degree (to rotate from -120 to 120).

The proposed algorithm contains three steps:

- Measurement: Construction of two one-dimensional array in memory of robot for distance and motor angle.
- Extraction: extract reliable data from measurement data with respect to reference frame.
- Calculation: Differentiate robot from object and identify position of robots.

Results show error of 2.6% at 1m distance. It is not as accurate as the Hokuyo sensor, but it still presents good results.

14.4 Notes

- Need for 360 degree FOV.

- Bat-like sensing system.
- Cost approx $50
- Commercial sensor $1200.
- Goals:
  - Use dual rotating infrared sensors (DRIr)
  - Operation function controlling observation motions by DRIr.
  - An observation algorithm to enable position estimation.
- Design goals:
  - Low cost
  - Compact
  - Easy integration
- Important to control DRIr:
  - Rotation speed
  - Intervals
  - Range
- DRIr built with two MiniStudio MiniS RB90 servo motors with 180 degrees of rotation and one Sharp GP2Y0A02YK infrared sensor.
- MobileRobots Pioneer 3-DX equipped with a pair of DRIr and laptop as main controller
- Sensing range up to 320cm.
- Rotation speed from 14.9 def/s to 154 deg/s.
- Ir emits ray at one or two degree interval.
- Front Ir scans from -120 degrees to 120 degrees.
- Base motor rotates 180 degrees, upper motor rotates 60 degrees.
- Three step algorithm:
  - Measurement
  - Extraction
  - Calculation
- Results show error of 2.6% at 1m distance.

14.5 Evaluation

The results of the sensor itself show that the design was successful, but there are a couple of limitations that need to be addresses in order to be useful in real life situations. First, the range is very small. Although authors claim that sensor is built for swarm applications, range of 1, is very small. This would constrain the robot to move at very slow speeds. Also, the design does not look robust. Since authors never address robustness of sensor, one can assume it is fragile.
Despite its limitations, it is certainly a low cost sensor. If authors can improve the design and range of sensor, it could potentially be useful for swarm application, that need low cost hardware.

15 Visual odometry: Part II: Matching, robustness, optimization, and applications. Fraundorfer, Scaramuzza. 2012

15.1 Reference

Fraundorfer, F., & Scaramuzza, D. (2012). Visual odometry: Part II: Matching, robustness, optimization, and applications. IEEE Robotics & Automation Magazine, (Vol. 19, Issue 2, pp. 78-90).

15.2 Abstract

Part II of the tutorial has summarized the remaining building blocks of the VO pipeline: specifically, how to detect and match salient and repeatable features across frames and robust estimation in the presence of outliers and bundle adjustment. In addition, error propagation, applications, and links to publicly available code are included. VO is a well understood and established part of robotics. VO has reached a maturity that has allowed us to successfully use it for certain classes of applications: space, ground, aerial, and underwater. In the presence of loop closures, VO can be used as a building block for a complete SLAM algorithm to reduce motion drift. Challenges that still remain are to develop and demonstrate large-scale and long-term implementations, such as driving autonomous cars for hundreds of miles. Such systems have recently been demonstrated using Lidar and Radar sensors [86]. However, for VO to be used in such systems, technical issues regarding robustness and, especially, long-term stability have to be resolved. Eventually, VO has the potential to replace Lidar-based systems for egomotion estimation, which are currently leading the state of the art in accuracy, robustness, and reliability. VO offers a cheaper and mechanically easier-to-manufacture solution for egomotion estimation, while, additionally, being fully passive. Furthermore, the ongoing miniaturization of digital cameras offers the possibility to develop smaller and smaller robotic systems capable of ego-motion estimation.

15.3 Summary

Fraundorfer and Scaramuzza (2012) present a tutorial/survey regarding visual odometry (VO). This paper is the second part that summarizes how VO detects and matches features using images, as well as the different types of approaches that currently exists. It also points the need for robustness and long term stability to be resolved in order to be used in applications such as autonomous driving.

Visual odometry is effective because it does not suffer from wheel slip on uneven terrain like wheel odometry does. Usually, VO is coupled with a GPS, IMUs, whell or laser odometry to prove more accurate trajectory. VO is specially important in GPS denied environments such as space and underwater exploration.

The tutorial mentions two main approaches for feature selection and matching:

- First one consists in finding features in one image and track them in following frames.
- Second one consists of independently detect features in all or several images and match them according to feature similarity.

VO is characterized for using corners or blobs as features. Using corner features is fast, but characteristics are less distinctive. Blob features are more distinctive, but are slower in comparison. Corner detectors include: Harris, Shi-Tomasi, and FAST. Blob detectors include: SIFT, SURF, and CENSURE.

Time steps can be used for additional constrains to improve camera pose. Error or pose uncertainty should be kept as small as possible to reduce drifting.

Current applications for VO include space exploration (Mars Rovers), UAV for tracking and reconnaissance, swarm projects, and automotive industry (assisted driving).

15.4 Notes

- VO not affected by wheel slip.
- Provide more accurate trajectory estimates with error within 0.1 to 2.0%.
- Supplements GPS, IMU, wheel and laser odometry.
- Important in GPS denied environments
- Two feature selection and matching approaches:
  - Finding features in one image and track them in following images.
  - Independently detect features in all images and match then according to similarities.
- VO characterized by corner or blob detectors.
- Corner detectors are fast but less distinctive.
- Blob detectors are more distinctive but slower.
- SIFT devised for object and place recognition with outstanding results.
- 2010-2011, three new descriptors:
  - BRIEF: brightness comparison
  - ORB: tackles orientation invariance.
  - FAST: allows scale and rotation invariance.
- To match features, compare feature descriptors between two images.
- Optimization:
  - Time steps to improve camera poses.
  - Loop constrains for pose-graph optimization.
  - Comparing similarities with past images.
- Applications:
  - Space exploration.
  - UAVs
  - Swarm projects
  - Autonomous underwater vehicles
  - Driver assistance (in development)

15.5 Evaluation

This paper summarizes the state of the art in visual odometry in a structured and informative way.

It is a known that Visual Odometry as a field is very important for robot localization. Optimization of VO by either low cost cameras of effective algorithm will help to bring low cost approaches for low cost robotics.

16 Visual Odometry. Nister, Naroditsky, Bergen. 2004

16.1 Reference

Nister, D., Naroditsky, O., & Bergen, J. (2004, June). Visual Odometry. In Computer Vision and Pattern Recognition, CVPR 2004. IEEE Proceedings of the Computer Society Conference on (Vol. 1, pp. I-I).

16.2 Abstract

We present a system that estimates the motion of a stereo head or a single moving camera based on video input. The system operates in real-time with low delay and the motion estimates are used for navigational purposes. The front end of the system is a feature tracker. Point features are matched between pairs of frames and linked into image trajectories at video rate. Robust estimates of the camera motion are then produced from the feature tracks using a geometric hypothesize-and-test architecture. This generates what we call visual odometry, i.e. motion estimates from visual input alone. No prior knowledge of the scene nor the motion is necessary. The visual odometry can also be used in conjunction with information from other sources such as GPS, inertia sensors, wheel encoders, etc. The pose estimation method has been applied successfully to video from aerial, automotive and handheld platforms. We focus on results with an autonomous ground vehicle. We give examples of camera trajectories estimated purely from images over previously unseen distances and periods of time.

16.3 Summary

Nister et al. present a system that is capable of motion estimation using video input from a moving camera called Visual Odometry (VO). It consists of detecting, tracking and matching features in image frames to estimate camera motion. This paper focuses on the application of VO for autonomous ground vehicles.

The first step of VO is detecting features in each frame of the video input. Harris corners are used as features because they are stable under small to moderate distortions in frame image. For the second step, features are matched between pair of frame that are within a certain distance from each other. Potential matched with highest normalized correlation is a preferred match. Only features that have each other as match are valid matches.

Valid matches are then linked to tracks over time. The resulting tracks are fed forward for geometry estimation. The authors have two methods for geometry estimation: one using monocular video as input, and other using stereo.

For testing, the vehicle was equipped with a Differential Global Positioning System (DGPS) and an Inertial Navigation System (INS) that will be used to compare estimations from VO. Comparing with DGPS, the overall path length showed an error of 1% to 5%. Since INS have incremental errors, VO and INS were compared using the yaw disparity between them, which resulted in an approximate zero mean, with standard deviation of 0.59 degrees.

16.4 Notes

- Motion estimation of moving camera based on video input.
- Feature tracking
- Used in conjunction with GPS, inertial sensors, wheel encoder, etc.
- Successfully applied to aerial, automotive and handheld platforms.
- Obstacle detection and mapping is performed using visual input, it becomes natural to use it to estimate motion.

- Feature detection:
  - Detect Harris corners in each frame (stable under small to moderate distortions)
  - Details such as order, storage, threshold, and filter taps can affect the result quality.
  - Image is represented in 8 bits per pixel
  - Compute strength of corner response to define feature points
  - limit number of selected features with local saturation.
- Feature extraction:
  - Feature points are matched between pairs of frames.
  - They match all features points that are within a certain disparity limit from each other. (10%)
  - disparity can be from 3% to 30%
  - Normalized correlation is used over a 11 x 11 patch to evaluate potential matches.
  - For each potential match, they compute scalar product between two patches.
  - Feature with highest normalized correlation is preferred match.
  - Only features that match each other are accepted as valid match.
  - Link accepted matches to tracks over time.
- Robust estimation:
  - Resulting tracks are fed forward to geometry estimation
    * Monocular scheme:
      1. Track features over a certain number of frames.Estimate relative poses between frames.
      2. Triangulate observed feature tracks into 3D points.
      3. Track certain additional number of frames and compute pose with respect to known 3D points
      4. Re-triangulate 3D points using first and last observation on image track (repeat step 3 a certain number of times)
      5. repeat from step 1 a certain number of times
      6. Insert firewall and repeat from step 1
      7. Firewall in this context means that subsequent frames after the firewall will be considered the first frame. (to protect against error propagation and buildup)
    * Stereo scheme:
      1. Match feature points between left and right images of stereo pair. Triangulate observed matches into 3D points.
      2. Track features for a certain number of frames. Compute pose of stereo rig.
      3. Repeat from step 2 a certain number of times.
      4. Triangulate all new feature matched using observations in left and right images. Repeat from step 2 a certain number of times.
      5. Retriangulate all 3D points to setup firewall. Repeat from step 2.
- system was equipped with a Differential Global Positioning System and an Inertial Navigation System
- No prior knowledge of motion was used to produce visual odometry.
- Comparing VO with DGPS showed an error between 1.07 to 4.86 in total path length in three different runs.
- Since VO and INS function incrementally by dead reckoning, they accumulate error over time.
- Test showed an approximate zero mean in yaw magnitude discrepancy between VO and INS.

16.5 Evaluation

The paper presented by Nister et al. describes a new method for motion estimation that produce results comparable to GPS and INS.

I consider that Visual Odometry is an important topic for low cost robotics, as it relies on cameras for motion estimation. The cost of GPS and INS can be high when comparing it to the cost of a good quality camera. As the authors mentioned: since obstacle detection and mapping is already performed using visual input, it is natural to also use it for motion estimation. this of course decreases the need for additional sensors and thus, decreases cost.

17 Development of a low cost anthropomorphic robot hand with high capability. Bae, S. W. Park, J. H. Park, Baeg, Kim, Oh. 2012

17.1 Reference

Bae, J. H., Park, S. W., Park, J. H., Baeg, M. H., Kim, D., & Oh, S. R. (2012, October). Development of a low cost anthropomorphic robot hand with high capability. In Intelligent Robots and Systems, IROS 2012. IEEE International Conference on (pp. 4776-4782).

17.2 Abstract

This paper presents a development of an anthropomorphic robot hand, 'KITECH Hand' that has 4 full-actuated fingers. Most robot hands have small size simultaneously many joints as compared with robot manipulators. Components of actuator, gear, and sensors used for building robots are not small and are expensive, and those make it difficult to build a small sized robot hand. Differently from conventional development of robot hands, KITECH hand adopts a RC servo module that is cheap, easily obtainable, and easy to handle. The RC servo module that have been already used for several small sized humanoid can be new solution of building small sized robot hand with many joints. The feasibility of KITECH hand in object manipulation is shown through various experimental results. It is verified that the modified RC servo module is one of effective solutions in the development of a robot hand.

17.3 Summary

Ji-Hun Bae et al. developed a low cost anthropomorphic robot hand that consists of four actuated fingers using RC servo modules. In their proposed method, they include all the electronic components inside the finger and palm of the robot hand. Due to this, the robot hand is approximately 1.5 times bigger than a real human hand. The robot hand consists of 3 fingers and a thumb to enable object grasping.

Each finger has 4 DOF for a total of 16 DOFs. The focus of this hand is miniaturization (size and weight) to be able to mount it on an arm. For this purpose, RC servo modules serve as joints and allow for simple wire connection that is not bulky. Since force and torque sensor is not present in fingertips, it was possible to control grasping with torque control of actuators. In total the robot hand weights 0.9 kg.

At the end of each finger, a soft silicone finger tip is added to allow for:

- absorbing impacts under collision between finger-end and an object.
- make are contact with an object
- avoid slip on the surface of grasped object.

Testing of robot hand showed robot hand to be able to grasp objects of 1.5 kg with 4 finger grasp and up to 2 kg with envelope grasp. It takes about 0.2 s to finish grasping process and 0.3 s to finish pinching process. Robot hand also keeps grasping object when unexpected small forces are applied to object.

17.4 Notes

- Development of anthropomorphic robot hand with 4 actuated fingers using RC servo modules.
- Their proposed method integrates actuators, gear, sensor and electronics into finger and palm while being relatively small and lightweight.

- KITECH hand consists of 3 fingers and one thumb.
- Robot hand is approximately 1.5 times bigger than a real human hand.
- each finger has 4 DOFs.
- Total weight: 0.9 kg.
- Fingertip is made of silicone:
  1. Absorbs impacts under collision between finger-end and an object.
  2. Make are contact with an object.
  3. Avoid slip on the surface of grasped object.
- Control is divided in two parts: main control and sub-control. Main control operated in an external PC and sub control is embedded in KITECH hand.
- RC servo module supports position, velocity, and torque control.
- Types of classification by Cutkosky taxonomy.
- Force/torque sensor not installed in fingertip .
- It was possible to control grasping force with torque control of actuators.
- Can grasp an object of 1.5 kg with 4 fingered grasping.
- Can grasp objects up to 2 kg with envelop grasping.
- Use groped grasping for internal force control.
- Object is assumed to be positioned in area to be grasped.
- Equilibrium of forces in each finger means the robot hand keeps grasping object.
- Takes about 0.2 seconds to finish grasping process and 0.3 to finish pinching process.
- Robot hand keeps grasping object when unexpected small forces are applied to object.

17.5 Evaluation

The proposed robot hand by Ji-Hun Bae et al. can be a good option for a robotic hand that is not very bulky and light weight enough. Also, the paper shows good results since the KITECH Hand can envelop, grasp, and pinch objects and hold it even under small disturbances. there are still some things that need further improvement, such as including force or touch sensor in the fingers or fingertips, and make it smaller to allow for precise manipulation, etc.

Robotic manipulators tend to be expensive because they need expensive actuators for it. This paper is relevant to low cost robotics because they manage to use low cost actuators in the form of RC servo modules to develop a working robotic hand.

18 First 3D printed medical robot for ENT surgery-Application specific manufacturing of laser sintered disposable manipulators. Entsfellner, Kuru, Maier, Gumprecht, Lueth. 2014

18.1 Reference

Entsfellner, K., Kuru, I., Maier, T., Gumprecht, J. D., & Lueth, T. C. (2014, September). First 3D printed medical robot for ENT surgery-Application specific manufacturing of laser sintered disposable manipulators. In Intelligent Robots and Systems, IROS 2014. IEEE/RSJ International Conference on (pp. 4278-4283).

18.2 Abstract

The Stapedotomy is a standard ENT (ear, nose and throat) surgery, where the surgeons use surgical micro hooks and forceps to replace the stapes with a small titanium implant. However, there are some challenges with this procedure. Especially, the non-ergonomic posture of the surgeon increases the hand tremor and leads to an inaccurate positioning of the implant. This may cause hearing loss and the patient may need a revision operation. In this paper, we present the first laser sintered disposable manipulator for ENT surgery, which allows the surgeon to move a micro hook in three directions via a joystick console, while his/her hands are located on an armrest. This may increase the surgical outcome by enhancing the ergonomics and therefore may reduce the number of revision operations. We show that the fabrication cost of the single-use robot does not increase the operation expenses drastically. To conclude, our preliminary evaluation with a middle ear phantom indicates that a basic surgical maneuver can be performed via the presented robotic system.

18.3 Summary

Entsfellner, et al. present a disposable robot system that can help surgical procedures such as ear, nose, throat surgery. They designed a 3D printed manipulator to avoid non-ergonomic postures and reduce potential accidents during surgery. Since it is a disposable manipulator, it avoids the need for maintenance and sterilization, thus reducing cost.

The robot system is comprised of four parts: a passive arm, the 3D printed robot with surgical instrument, a joystic console, and the control box. The manipulator has a 20 x 20 x 20 mm^3 working area with 3 translational DOF. The 3D printed structure contains a mount for a passive arm an instrument mount and three linear modules that act as joints.

The joints consists of a sliding bar with four flexible semicircular elements and a stiff rectangular frame. Semicircular elements work like drag chains. Different measurements allow for specific stiffness, and for that, they have a customization tool to find out the optimal geometrical parameters of the joint's width, height, and length for a desired stiffness.

Robot was evaluated in a set of perforation tasks and applying a specific force. Other constraints such as time were ignored. Trials showed that failure rate using the 3D printed manipulator is half of the failure rate of the manual procedure. Results support that the disposable robot is more accurate than manual procedure.

18.4 Notes

- Disposable manipulator for ear, nose and throat(ENT) surgery.
- Does not increase operation cost drastically.

- It aims to enhance ergonomics during surgery to increase surgical outcome and therefore reduce risk for patient.
- Related work is too expensive and include other costs such as sterilization and maintenance.
- Specifications:
  - 3 translational DOF with 20 x 20 x 20 mm^3 (with rotation).
  - Instrument mount.
  - Passive arm mount.
  - Max size of 200 x 80 x 80 mm^3.
  - Monolithic single use body.
  - Integrated laser sintered compliant mechanisms for linear guides.
  - Single use motors with easy mounting.
- Robotic system consists of four parts:
  - Passive arm.
  - 3D printed robot.
  - Joystick console.
  - Control box.
- 3d printed structure has a passive arm mount, instrument mount and three identical linear modules.
- Linear modules consist of compliant joint and stepper motor fixture each and fabricated in one piece.
- Axes of of the robot are position controlled by separate axes of the robot
- Made from polyamide 12. Suitable for large deformations without breaking.
- Linear joint consists of sliding bar, four flexible semicircular elements and a stiff frame.
- Nanotech LSP2575 stepper motors allow for single use as they are cheap and small in size.
- Maxon EC16 would be an option for reusable motor.
- Perforation task using the 3D printed robot showed better results than manual preparation.
- Of 49 trials, 42 contacted all holes.
- In force application trials, 40 were successful.
- Results support hypothesis that accuracy of robot is sufficient.
- Failure rate of disposable robot is half of the failure rate from manual manipulation.

18.5 Evaluation

The paper presented by Entsfellner, et al. show promising work for low cost robotics. As authors mentioned, there are not many manipulators to aid in surgical procedures, and the available ones are usually expensive. It is good that trial results reduce failure rate compared to manual procedures, but sample size was too small to consider this manipulator commercially available, specially if it will be used for medical purposes.

19 Low-cost collaborative localization for large-scale multi-robot systems. Prorok, Bahr, Martinoli. 2012

19.1 Reference

Prorok, A., Bahr, A., & Martinoli, A. (2012, May). Low-cost collaborative localization for large-scale multi-robot systems. In Robotics and Automation, ICRA 2012. IEEE International Conference on (pp. 4236-4241).

19.2 Abstract

Large numbers of collaborating robots are advantageous for solving distributed problems. In order to efficiently solve the task at hand, the robots often need accurate localization. In this work, we address the localization problem by developing a solution that has low computational and sensing requirements, and that is easily deployed on large robot teams composed of cheap robots. We build upon a real-time, particle-filter based localization algorithm that is completely decentralized and scalable, and accommodates realistic robot assumptions including noisy sensors, and asynchronous and lossy communication. In order to further reduce this algorithm's overall complexity, we propose a low-cost particle clustering method, which is particularly well suited to the collaborative localization problem. Our approach is experimentally validated on a team of ten real robots.

19.3 Summary

Prorok et al. present a method to localize a team of robots using a particle clustering approach. Their proposed method has low computation and sensing cost requirements. Previous work on the field has high computation cost or rely on communication without information loss to work. The particle clustering method in their approach summarizes a set of X with M particles to a set X' of K clusters, which reduces computation cost significantly (linear to the number of clusters).

For the team of robots navigating in a certain area, a robot can communicate with another close by robot and transmit a calculated range and bearing to the first robot. Every robot will be running a collaborative particle filter. All received information from a detected robot will be considered as a set of observations for the robot. Their detection model describes the probability that a robot will detect another robots pose given the detection information.

They sample the distribution according to the detection model (independent from previous belief), so that poses are more likely to be drawn at poses from observations. Dense particle sets are clustered to reduce the computation required to compute probability for detection model. Total cos of algorithm is MK (M = number of particles, K = number of clusters.)

The localization algorithm was tested in a team of ten robots, equipped with wheel encoders for self localization. Initially only one robot knows its position and the rest are "lost". Test result showed that more particles lead to a better approximation. More clusters also had the effect of lowering the divergence from the measured probability.

19.4 Notes

- Localization with low computational and sensing requirements for large robot team deployment.
- Robots start in unknown initial position
- Particle clustering method
- Previous work regarding multi robot localization requires high computational resources, rely on communication without packet loss, or are centralized systems (not scalable).

- Robots make no use of exteroceptive sensors capable of feature recognition.
- Every robot runs a collaborative particle filter.
- Multi Robot MCL:
  - Robot R_n detects robot R_m and simultaneously receives localization information from R_m
  - If several robots communicate, then the received information is the set of all relative observations of R_n.
- Detection model: Describes probability that R_m detects R_n at pose x_n, given detection data d_{mn}
- Reciprocal sampling: Samples are draw in poses which are probable given the robot observations, which are independent from previous belief.
- Particle clustering:
  - Clustering particles sets allow for computational and communication resources to be reduced.
  - The goal of clustering is to reduce number of operations needed to compute the probability density of the detection model.
  - Summarizes a set of X composed of M particles to a set X' composed of K cluster centroids, thus, reducing computation cost to MK (Linear).
  - Clustering algorithm is non-iterative, order-independent, non-parametric that produces a predefines number of K clusters.
- Experiments were conducted in ten Khepera III robots.
- Setup consists of a 3m large empty square area.
- Robots were equipped with wheel encoders and use odometry for self localization.
- Experiments were tested for 3.5 minutes where one robot was localized while the remaining one are "lost".
- Data is comprised of inter robot detection and odometry readings.
- Detections are made asynchronously every 5 s.
- Results show that larger particle sets contribute to more accurate localization.
- The more clusters employed in clustering algorithm, the smaller the divergence to the true probability measured.

19.5 Evaluation

The paper presented by Prorok et al. showed promising results. Their algorithm is able to successfully localize several robots using only wheel odometry and communication information. Localization is usually a problem for robots with low computational capabilities, and as such I consider this paper relevant to low cost robotics because does not require high computational resources and is able to work with little information.

20 Low-cost vision-based AUV guidance system for reef navigation. Dunbabin, Corke, Buskey. 2004

20.1 Reference

Dunbabin, M., Corke, P., & Buskey, G. (2004, April). Low-cost vision-based AUV guidance system for reef navigation. In Robotics and Automation, ICRA 2004. IEEE International Conference on (Vol. 1, pp. 7-12).

20.2 Abstract

Ensuring the long term viability of reef environments requires essential monitoring of many aspects of these ecosystems. However, the sheer size of these unstructured environments (for example Australia's Great Barrier Reef) pose a number of challenges for current monitoring platforms which are typically remote operated and required significant resources and infrastructure. Therefore, a primary objective of the CSIRO robotic reef monitoring project is to develop and deploy a large number of AUV teams to perform broadscale reef surveying. In order to achieve this, the platforms must be cheap, even possibly disposable. This work presents the results of a preliminary investigation into the performance of a low-cost sensor suite and associated processing techniques for vision and inertial-based navigation within a highly unstructured reef environment.

20.3 Summary

Dunbabin, et al. present a paper that describes a guidance and navigation system for underwater monitoring. The localization is done with visual odometry, using two simultaneous cameras for feature detection. The requirements for the system are: should be compact, low cost (less than $10,000 AUS), maneuverable, able to navigate on underwater unstructured environments.

The system is composed of two color CMOS sensors for visual odometry, an IMU which features angular rates, acceleration, magnetometers, altitude and GPS. Pressure sensor and a computer running Linux to process all sensor information.

There are two main issues involved in using cameras for underwater navigation. First they need to calibrate cameras to accurately estimate height above sea floor. Also, cameras suffer from refraction underwater. To keep low cost, an algorithm is used for refractive correction rather than using expensive lenses for correction. The algorithm uses pixel displacement in images between the two cameras to determine range and used for height estimation (from sea floor).

Since the vehicle need to travel to different goals and end in its starting position, it needs to localize itself. For this, standard visual odometry is used. For this, several assumption were made: heading and starting positions are known, the vehicle only translates in 2D and is able to rotate, height from sea floor is known, and environment is feature rich. Standard for this algorithm, 100 features are used in each iteration. The system was not tested in real underwater environment. Future work includes equipping and an underwater UAV to test system.

20.4 Notes

- Need for a fast way to monitor underwater ecosystems.
- Previous UAVs are generally large and expensive or are usually for shallow water.
- Some of them still require human operators.
- Typical sensors used: sonar, inertial, pressure and underwater telemetry.
- Vision allows for navigation, station keeping as well as provision of manipulation feedback information; but dependent on visibility and lighting.

- Evaluation of low cost vision based sensor for underwater navigation.
- Requirements:
  - Ability to navigate on unstructured surface at fixed heights.
  - Small and compact.
  - Maneuverable.
  - Must operate at close range.
  - Operation depth of 100 m.
  - Low cost (less than $10,100 AUS).
- IMU used features angular rates, acceleration, magnetometers, altitude and GPS.
- Camera is a color CMOS sensor; it is cheap but enough for the task.
- Camera calibration:
  - Camera was used because it does not suffered from reflection like sonar sensors and can determine height and features for obstacle avoidance.
  - Sufficient lighting is assumed for testing
  - Two cameras mounted, record half vertical image.
  - Horizontal disparity is calculated.
- Refractive Correction:
  - An algorithm is used to avoid the need of using refractive correction lenses on the cameras.
  - The actual range can be derived from the angles measured from pixel displacement in left and right cameras.
- Local position estimation:
  - Assumptions:
    - Start position and heading known.
    - Only 2D translation with rotation.
    - Known height.
    - Sufficiently feature rich targets. (Harris corners)
  - Algorithm steps:
    - Collect image.
    - Find features.
    - Take 100 most dominant features.
    - Match features with normalized cross correlation.
    - Estimate velocity and direction for each matched feature.
    - Cluster magnitude and direction of image velocities.
    - Reject Out-lier velocities and calculate mean.
    - Scale image velocity to world velocity.
    - Integrate world velocity to determine displacement.
    - Repeat from step 1.
- Result show that it works on controlled environments.

20.5 Evaluation

Dunbabin, et al. present a paper to prove a system that is capable of underwater navigation using visual odometry. Their results show that it works in their tests, but there are a number of issues that can be problematic. First of all, this was not tested in a real underwater environment. Although testing showed good result, actual implementation can be different from tests. Also, testing was made under several assumptions that may or may not hold in actual implementation, such as sufficient lighting for cameras or sufficient features to extract.

Test were also made in a controlled environment, and since the paper's initial claim is that the system will be used for reef navigation, so it leave more room for failure because of unexpected events. The proof of concept show good results, but there needs to be more research and testing before implementation.

21 Motion reconstruction with a low-cost MEMS IMU for the automation of human operated specimen manipulation. Antonello, Nogarole, Oboe. 2011

21.1 Reference

Antonello, R., Nogarole, I., & Oboe, R. (2011, June). Motion reconstruction with a low-cost MEMS IMU for the automation of human operated specimen manipulation. In Industrial Electronics, ISIE 2011. IEEE International Symposium on (pp. 2189-2194).

21.2 Abstract

We consider the problem of automating the motion performed by a human operator when manipulating a specimen in tasks such as visual inspections for defects. This is a typical situation in which the trajectory of the manipulated object is hardly described by analytical functions, since the actual movements are suggested more by the operator's experience, rather than a standardized protocol. In principle, traditional motion capture systems based on computer vision methods could be employed to reconstruct the motion: however, especially when manipulating small specimens, visual occlusions caused by the operator's hand prevent the correct tracking of the moving object. In this paper, we investigate the possibility of reconstructing the motion by using the information provided by a low-cost MEMS Inertial Measurement Unit (IMU) attached to the specimen. For simple manipulating tasks such as shaking and rotations, we show that the motion capture system based on inertial measurements can be effectively used.

21.3 Summary

Antonello, et al. claim that a low cost IMU can be used for motion reconstruction of a human operator when manipulating an object. The main focus of this paper is to recreate simple tasks such as shaking or rotation and not to actual product engineering. They explain disadvantages of other methods such as using cameras that suffer from visual occlusion, exoskeletons that are bulky and uncomfortable, and electromagnetic sensing which is not suitable for industrial environments.

Since the IMU is attached to a manipulator, a transformation is needed to convert between inertial frame and body frame. Displacement is calculated by integrating accelerometer outputs. To avoid systematic erros, initial calibration is needed. Calibration consists on finding a transformation to transform sensor measurements into components of a sphere. Least square means is used with 6 observations.

Attitude is then estimated using and Extended Kalman Filter to correct the attitude prediction from integrating the gyroscope output. Magnetometers included can be used reduce noise from estimates from gyroscope measurements.

Accelerometer integration is used for displacement only and not for actual positioning in space. For testing, IMU was mounted in end effector or a robot arm. Regarding attitude, there is an alignment problem of the inertial frame and the body frame. This means displacement in all axis will not be exactly same.

Testing showed estimated vs actual shaking motion displacement, but no concrete numbers were provided. Attitude was also explained with a graph and not actual numbers.

21.4 Notes

- Automating motion of human operator for task such as visual inspection.
- IMU over camera because hands can obstruct vision on small specimens.

- Automating repetitive tasks can improve speed and cost.
- Optical systems suffer from visual occlusions as well as absence of distinctive features can affect results.
- Exoskeletons can be uncomfortable to wear, and limit human dexterity.
- Electromagnetic sensing is unsuited for industrial environments.
- IMU Calibration:
  - A coordinate transformation is required to obtain inertial frame from moving frame.
  - Scale factors and non-orthogonality errors must be accounted.
  - Requirement for triad calibration is that the quantity measured needs a constant magnitude.
  - Given a set of n measurements, find A and b using least mean squares between sensor measurement and reference magnitude.
- Motion reconstruction:
  - Drift still present after calibration, can be compensated by correcting estimate.
  - Magnetometers are used to correct attitude estimate obtained from gyroscope measurements.
  - Attitude is defined as orientation with respect to some reference frame.
  - A matrix is defined to transform between two frames.
  - Triad of gyroscopes' frames attached to body frame need to be aligned with body frame.
  - Extended Kalman Filter is used to estimate body attitude and gyroscope measurement bias.
  - Overall steps include:
    * State vector propagation.
    * Error covariance matrix propagation.
    * Innovation computation.
    * Kalman gain computation.
    * State vector update.
    * Error covariance matrix update.
- Focus on motion reconstruction, not in actual product engineering.
- If dimensions and weight are a main concern, IMU should be changed.
- Six orientations were sufficient for calibration.
- For testing, IMU was mounted in a robotic arm's end effector.
- IMU is not perfectly aligned, so components of displacement are not zero in y and z axis.
- Gyroscope does not accumulate attitude error over time, but magnetic distortions can affect.

21.5 Evaluation

Results provided by Antonello, et al. are lacking additional information. There is no mention of how testing was executed and for how many trials. No actual numbers or percentages were provided to compare estimates with actual displacements.

This paper is relevant to low cost robotics as they are using a low cost IMU for their motion reconstruction. The system is limited in the sense that in can only reconstruct such as shaking and rotation, and is not suited for precise movement needed in industrial environment where this system would be needed.

22 A low cost embedded color vision system. Rowe, Rosenberg, Nourbakhsh. 2002

22.1 Reference

Rowe, A., Rosenberg, C., & Nourbakhsh, I. (2002, October). A low cost embedded color vision system. In Intelligent Robots and Systems, IROS 2002. IEEE/RSJ International Conference on (Vol. 1, pp. 208-213).

22.2 Abstract

In this paper we describe a functioning low cost embedded vision system which can perform basic color blob tracking at 16.7 frames per second. This system utilizes a low cost CMOS color camera module and all image data is processed by a high speed, low cost microcontroller. This eliminates the need for a separate frame grabber and high speed host computer typically found in traditional vision systems. The resulting embedded system makes it possible to utilize simple color vision algorithms in applications like small mobile robotics where a traditional vision system would not be practical.

22.3 Summary

Rowe, et al. present an embedded color vision system using a low cost camera and microprocessor. The overall cost of the system is 109 USD. The vision system runs at 16.7 frames per second and is able to successfully track blobs of colors from image frames. Tracking can be custom bounded to a specific color.

Since the system utilizes a microcontroller with low RAM, it can not buffer any frame data. To achieve this, frame rows are sent one by one until covering complete image. The system works by comparing the RGB bound color to pixels. Position of detected pixels that fall within bound are accumulated, and centroid is calculated from average. To reduce noise, two adjacent pixels are required within same bounded color is required to detect a pixel.

A settings interface to change how data flows through system is added. A small window can be set to capture specific region of image. An GUI interface displays system statistic and data in real time. A demo mode is included, which track first object at sight upon power up.

To test system, an object was tracked for 10,000 frames and showed very litter jitter. It was also tested outdoors with sunlight with near identical results.

22.4 Notes

- Low cost embedded vision system for color tracking at 16.7 fps.
- Low cost CMOS color camera processed by high speed, low cost microcontroller.
- Full system costs 109 USD.
- Three chip design: camera, microcontroller, level shifter.
- Data bus and synchronization pins directly connected to microcontroller for real time processing.
- Dimensions: 1.75" h x 2.25" w x 2" d
- 352 x 288 resolution at 60 fps.
- Microcontroller operates at 75 MHz but has low memory (136 bytes of RAM)
- Limited to horizontal resolution of 80 RGB pixels.

- RGB bound is used to track and compare it against each pixel.
- Number of pixels within a color bound and area is computed.
- Position of pixels accumulate and divided by total number of pixels detected to calculate area centroid.
- A color statistics acquisition function return mean color.
- Can be used for motion detection.
- Window size to capture image region.
- To decrease noise, two adjacent pixels within same color range should be processed. Can cause small objects to not be detected.
- Interface settings to control how data flows into and out of the system: ASCII, binary, and poll mode return one packet of data at a time.
- Demo mode track object upon power up by controlling one servo motor.
- Frame dump for selecting image specific color to track.
- A full frame dump takes 5 seconds.
- GUI display graphical data in real time.
- Performance tested by tracking object in foxed position for 10,000 frames.
- Result show average jitter of 0.005 and 0.011 pixels in x and y respectively.
- Average tracked pixels were 144 with 0.16 standard deviation.
- Testing in daylight showed near identical results.
- Placed on a differential drive robot to track object for distances up to 15 feet.

22.5 Evaluation

The approach presented by Rowe, et al. works as expected and showed good results. Although the system is only tracking color, it can be extended to use it as object follower or object tracking. This paper is relevant because it is using low cost components to achieve it. It could be possible to improve the system and even reduce cost by using cameras and microcontrollers with better specifications than the ones used.

23 Low-cost intelligent static gesture recognition system. Sekar, Rajashekar, Srinivasan, Suresh, Vijayaraghavan. 2016

23.1 Reference

Sekar, H., Rajashekar, R., Srinivasan, G., Suresh, P., & Vijayaraghavan, V. (2016, April). Low-cost intelligent static gesture recognition system. Systems Conference, SysCon 2016. Annual IEEE International (pp. 1-6).

23.2 Abstract

This paper presents prototype implementation of low-cost, open hardware, static - gesture recognition system. The implemented system has three major components: A Glove and Sensor Unit (GSU) - consisting of a pair of gloves embedded with custom made, low-cost flex and contact sensors, a Primary Supporting Hardware (PSH) that maps change in input values from GSU, a Secondary Supporting Hardware (SSH) that processes the input values and recognizes the gesture accurately. When a gesture is signed, the GSU tracks the change in orientation of the fingers, which results in a change in voltage levels of the sensors. This change is mapped by the PSH and passed on to SSH which comprises of two ATmega328P microcontrollers, one connected to each of the glove. The two microcontrollers are connected in a master-slave configuration and communication between them is facilitated through an XBee module. The performance of this gesture recognition system is evaluated using a data set comprising of 36 unique gestures. These gestures represent a total of 120 gestures that include all gestures across five globally used sign languages. A gesture recognition engine that resides in the master microcontroller processes the input and identifies the gesture. The gesture recognition engine comprises of a two stage selection-elimination embedded intelligence algorithm that is used to enhance the system efficiency from 83.1% to 94.5% without any additional hardware. The cost of the system is USD 30, which the authors believe on commercialization, could be brought under USD 9.

23.3 Summary

Sekar, et al. present a low cost hand gesture recognition system that can be useful for hearing impaired people. Considering the five main sign languages, a total of 120 gestures can be recognized. Their system uses of-the-shelf parts for easy implementation and costs approximately 30 USD. Authors claim that cost can be brought down to 9 USD after commercialization. System is made from a pair of gloves with and array of flex and contact sensors used to detect orientation change and contact.

Nine flex sensors and eight contact sensors are enough to capture all gestures. Five flex sensors are needed on top of glove and the remaining are placed in the bottom part. A contact sensor was placed on each fingertip, two on bottom part of palm and one on top. The system works by detecting change is orientation and sending voltage values to PSH and then multiplexed to SSH for further processing. Threshold value for voltage was added to one glove to avoid overlapping values for different gestures.

The array of sensors are subdivided into three blocks. The gestures are represented with two bitmaps corresponding to each glove. There are two operating modes for gesture recognition: DOM and IOM. DOM exactly matches each of the three blocks. IOM uses a two step elimination process where the first step is to match block B_2 and B_3 and obtain a selection table, then match the B_1 with B_1 block of selection table.

From 120 available gestures, 36 are unique, and thus used as master set. Testing for master gestures showed an efficiency of 83.1% in DOM and 94.5% in IOM in 100 trials for each gesture. Overall efficiency was 82.9%, testes across ten dataset of 1000 trials each.

23.4 Notes

- Implementation of low cost static hand gesture recognition system.
- Consists of three components: Glove sensor unit (GSU), Primary Supporting Hardware (PSH), Secondary Supporting Hardware (SSH).
- Include 120 gestures across all 5 globally used sign languages.
- Cost of system is 30 USD. Can be brought down to 9 USD.
- As of 2015, about 70 million people use sign language as first language.
- Previous work is usually expensive and complex systems.
- Built from off-the-shelf components for easy implementation.
- Gloves are embedded with custom made flex and contact sensors.
- Change in orientation of gloves is recognized and sent to PHS.
- PSH changes voltage level in sensors and passed to SSH.
- SHH processes values and identifies corresponding gesture.
- Gestures are displayed in an LCD.
- GSU:
  - Flex sensor costs 0.02 USD.
  - 17 sensors were required to map all gestures. (9 flex and 8 contact sensors)
  - 5 flex sensors capture change in orientation on top part of glove, while remaining capture bottom part.
  - Contact sensors are placed on each fingertip, plus two resting on bottom palm and one on top.
  - Flex sensor calibration is done by main microcontroller.
  - A final threshold is calculated between initial (not bent) and max (bent) threshold with 20% tolerance.
  - Contact sensors used a tolerance of +/- 0.05 V for calibration.
- PSH:
  - Voltage values are directly received from sensors.
  - Output is multiplexed and sent to SSH.
  - To avoid overlapping values for different gestures, thresholds were set for contact sensors in one of the hands. (1.8 V)
- Gesture sets:
  - From 120 available gestures across all 5 main sign languages, 36 are uniques, thus forming the master set.
  - Each gesture is represented by two bitmap (one for each hand) values.
- Two stage elimination:
  - Gestures are divided into blocks B_1, B_2, and B_3.
  - B_2, and B_3 are matched first.
  - B_1 is matched with corresponding values of lookup table.
- Gesture recognition engine:

  - Can run in one of two modes: Default (DOM) and Intelligent Operating Mode (IOM).
  - Default: matches gestures exactly with blocks B_1, B_2, and B_3.
  - Intelligent: Uses two stage elimination.

- Results:
  - 83.1% efficiency in DOM and 94.5% in IOM in 100 trials for each of 36 gestures.
  - Efficiency for individual gestures varied from 64% to 97%. 13 Gestures were undetected.
  - Overall efficiency was 82.9% across ten dataset each 1000 gestures each.

23.5 Evaluation

The system described by Sekar, et al. is relevant for low cost robotics because it is very cheap alternative compared to other relevant work. They avoid gyroscopes and accelerometer present in similar systems and use only custom low cost sensors. If what authors claim about the possibility of reducing the cost to 9 USD after commercialization, it could potentially be widely adopted.

There is only one issue that is not addressed in the paper and that is that they do not mention how heavy or light it is. They also do not show were the microcontroller that processes information is located.

24 Low-Cost Sensor System Design for In-Home Physical Activity Tracking. Nambiar, Nikolaev, Greene, Cavuoto, Bisantz. 2016

24.1 Reference

Nambiar, S., Nikolaev, A., Greene, M., Cavuoto, L., & Bisantz, A. (2016, December). Low-Cost Sensor System Design for In-Home Physical Activity Tracking. IEEE Journal of Translational Engineering in Health and Medicine (Vol. 4, pp. 1-6).

24.2 Abstract

An aging and more sedentary population requires interventions aimed at monitoring physical activity, particularly within the home. This research uses simulation, optimization, and regression analyses to assess the feasibility of using a small number of sensors to track movement and infer physical activity levels of older adults. Based on activity data from the American Time Use Survey and assisted living apartment layouts, we determined that using three to four doorway sensors can be used to effectively capture a sufficient amount of movements in order to estimate activity. The research also identified preferred approaches for assigning sensor locations, evaluated the error magnitude inherent in the approach, and developed a methodology to identify which apartment layouts would be best suited for these technologies.

24.3 Summary

Nambiar, et al. present a paper that studies the feasibility of using low cost sensors to monitor or predict activity inside a house. The study consist on determining how many sensors are needed and what is the optimal placement to get enough reliable information to determine activity levels inside a house. Authors bring this problem because sedentary living is a top ten cause of deaths worldwide. Their motivation is that it can be used to monitor elderly people whose physical, sensory and cognitive capabilities are decreasing.

Activity data from ATUS was used to training their model. The activity data is coded and captures activities from 148,000 Americans from 2003 and 2013. Data contains information such as location, duration, and start and stop times. Activity codes are assigned to locations. To relate locations with movement between rooms, a connectivity graph was created where nodes represent room and weights are assigned to edges representing the number of times a person traveled between rooms.

Programming model was constructed to study percent of activity level that can be detected by minimal number of sensors placed. Results showed that 59% was detected for two sensors, 85% with three, and 97% with four. An optimization study determined the optimal placement of sensors across doorways to detect maximum distance traveled of a person. The study showed errors less than 25%.

Main limitation is that straight line distance is assumed for distance traveled. Also, floorplan is not incorporated in the model even though it can impact reliability of data.

24.4 Notes

- Sedentary living is a top ten cause of deaths worldwide.
- Older adults face decrease in physical, sensory and cognitive capabilities which make human interaction difficult.
- Possibility to collect sufficient data to predict movement of old people.
- Find optimal spots to place sensors.

- Two types of monitoring: active and passive.
- Active involves wearable technology to track and gather physiological information. Not designed with old people in mind.
- Active need to be turn on and taken care of. Accidental movement can produce unwanted results.
- Passive involves using sensors placed around the environment that does not interfere with the person.
- Need to determine number and placement of sensors.
- Main problems addressed:
  - If doorway based system with low cost sensors is useful for predicting in home activity.
  - If errors can be characterized by sensor number and placement.
- Activity data provided by US Bureau of Labor Statistics.
- Set of location identified by analyzing senior apartment layouts.
- Each activity and location has a code.
- Connectivity graph captures the relationship between movements in different rooms.
- Node represents room.
- Weights are assigned to edges according to sequence of visited rooms.
- Studies for optimal sensor placement showed two sensors detected 59% of all activity, 85% with a third sensor and 97% with a fourth one.
- Infer traveled distance with number of passes between doorways. (sensors placed at some and not all doorways.)
- Distance can be calculated as a linear function of the number of passes between each doorway.
- 1500 fata points from ATUS dataset was used for training, and 893 for testing.
- Approximate effectivity of 0.92 on average for 3 sensor placement locations.
- Less than 25% error from calculated distance to actual distance.
- Regression analysis is robust enough to work under incorrect activity assignment for a certain location.
- Distance calculations assume straight line travel.
- Floorplan in not incorporated in the model.
- Future work includes monitoring rehab patients.
- Floorplans can have an impact on reliability of data.

24.5 Evaluation

The approach proposed by Nambiar, et al. is a paper relevant to low cost robotics, because the main focus is to demonstrate the feasibility of using low cost sensors to track activity inside a home. Their work shows that it is feasible to use a small array of low cost sensors to track activity inside a home.

While robust, their approach has some limitations that needs work, such as incorporating floor plans to their model. If authors can work on a floorplan design that increases performance and reliability of system, it could potentially be widely adopted by rehabilitation centers that need to monitor their patients at home.

25 Low-Cost Disposable Tactile Sensors for Palpation in Minimally Invasive Surgery. Naidu, Patel, Naish. 2016

25.1 Reference

Naidu, A., Patel, R., & Naish, M. (2016, November). Low-Cost Disposable Tactile Sensors for Palpation in Minimally Invasive Surgery. IEEE/ASME Transactions on Mechatronics (Vol. 22, Issue 1, pp. 127-137).

25.2 Abstract

Robot-assisted minimally invasive surgery prevents surgeons from manually palpating organs to locate sub-surface tumors and other structures. One solution is to use ultrasound; however, it is not always reliable. Tactile sensor arrays have been proposed as an alternative or complementary modality, but current designs have drawbacks including a large number of wires, lack of autoclavability or disposability and high cost. In this paper, four mass-producible, low-cost, sterilizable tactile sensor array designs with minimal wires are presented. Both piezoresistive and capacitive versions have been designed, each with a 2 2 mm spatial resolution and a scan rate of 30 Hz. Two sizes with 48 or 90 sensing elements are presented for each version. The sensing elements can measure contact pressures with 1 kPa resolution and they have over 84% accuracy in the 25150 kPa range. The low cost allows the sensors to be made disposable, avoiding the deterioration in performance resulting from repeated autoclaving. The sensors include the analog-to-digital conversion circuit onboard, requiring only two power lines and two digital signal lines to connect them. The small number of output wires allows the sensors to be incorporated into robotic surgical instruments with articulated wrists that do not have the space for a large number of wires. Both sensor versions are shown to be able to detect 6 mm diameter tumors at a depth of 10 mm in a silicone phantom and in ex vivo tissue samples.

25.3 Summary

Naidu, et al. present two different tactile sensors that can be used for minimally invasive surgery (MIS) and detect tumors. Sensors are designed to be low cost, sterilizable, disposable and mass producible. For each sensor, a large and small version was designed. Large version costs 35 USD while the small version costs 22 USD.

Tumors can be detected by measuring differences between its stiffness and that of tissue. Four types of tactile sensors were discussed: optical, piezoelectric, piezoresistive, and capacitive. Authors used piezoresistive and capacitive for their sensors. Piezoresistive sensor measures the change in resistance between two electrodes when pressure is applied. The capacitive measures capacitance between electrodes. Only the large prototype for both type of sensors were developed and tested. It is assumed small versions will work similarly.

Sensors needed a custom made printed circuit board because electrodes are placed on top and bottom, which need circuit end to be covered. A protective medical adhesive tape covers components and makes it waterproof to some extent (not completely). Heat sterilization is not recommended due to possible damage to components. Gamma and ozone based sterilization is recommended and better if sensor is mass produced in factory. Sterilization method is not tested.

Results showed an approximate accuracy of 85% and repeatability of 87% between the two sensors for 2 mm x 2 mm contact area; accuracy of 78% and repeatability of 77% for 4 mm x 4 mm contact area. Six individuals were trained to test sensors with real tissue (bovine). Experiment was done successfully for all individuals. Tumors were successfully detected at 10 mm depth.

25.4 Notes

- Robot assisted minimally invasive surgery (MIS) prevents surgeons to directly touch patient's organs.
- Ultrasound is not always reliable. Images obtained can be of poor quality.
- Design 4 tactile sensors that are disposable, sterilizable, low cost, and mass producible.
- Can detect 6 mm tumor in 10 mm depth.
- Tumors and blood vessel stiffness is different from tissue stiffness.
- Previous work lacks disposability, are expensive, has a large number of wire.
- Design must ensure palpated tissue is not damaged.
- Four classes of tactile sensors: optical, piezoelectric, piezoresistive, and capacitive.
- Optical: tend to have poor spatial resolution. Optic fiber's bending is limited. Not easily replaced.
- Piezoelectric: measure charge or electrical impedance of material to determine applied pressure. Complex analog signal processing required.
- Sensing principle:
  - Piezoresistive: resistance between electrodes decreases with applied pressure. Analog to digital conversion.
  - Capacitive: capacitance between electrodes increases with applied pressure. Capacitance to digital conversion.
- Small sensor costs 22 USD. 24 mm x 8 mm sensing area.
- Large sensor costs 35 USD. 36 mm x 10 mm sensing area.
- Only large sensor developed and tested.
- Sensor can reliably detect tumor about 70% of sensing area length.
- Custom pseudo-three-layer printed circuit board to include in sensor structure.
- Protective layer is added to cover components and to sterilize sensor.
- Leukoplast Sleek LF medical adhesive tape found to be sufficient.
- Sterilization techniques not tested. It is not known if sensor components will be damaged.
- Sensing pad is calibrated to sense up to 0.6 N, with 0.004 N resolution.
- Relationship between resistance of material and applied pressure is calculated by a quadratic function.
- Capacitance is inversely related to distance between electrodes.
- A device was developed to evaluate each sensing element.
- Results for 2 mm x 2 mm contact area:
  - Piezoresistive: 87% accuracy; 86% repeatability.
  - Capacitive: 84% accuracy; 88% repeatability.
- Results for 4 mm x 4 mm contact area:
  - Piezoresistive: 78% accuracy; 78% repeatability.

  - Capacitive: 76% accuracy; 79% repeatability.

- 16% and 8% drift due to stress relaxation for piezoresistive and capacitive respectively.
- Calibration involves palpating area without tumor.
- Data is sent wireless to computer and display palpating force in blue, red, and green. (low, high and optimal pressure respectively)
- 6 mm diameter silicone spheres simulated tumors.
- Testing at depth 2, 4, 6, 8, and 10 mm. Sensors easily detect all five different depths.
- Six persons were trained for real tissue (bovine) testing. All subject correctly identified tumor in tissue.

25.5 Evaluation

Sensors presented by Naidu, et al. successfully work as expected. Prototypes were tested with simulated and real tissue and achieve high accuracy and repeatability.

Some aspects need further work, such as finding a suitable protective material, as the adhesive tape can not completely make it waterproof, which will be needed for real applications. Since components can be affected by heat sterilization, other methods need to be researched and tested, which are not completely covered in this work. It is only mentioned that gamma and ozone sterilization will not affect components.

This paper is very well structured. Also, authors provide sufficient information and overview of the whole process from problem formulation all the way to testing and results without skimping on details.

26 Vision-based autonomous mapping and exploration using a quadrotor MAV. Fraundorfer, Heng, Honegger, Lee, Meier, Tanskanen, Pollefeys. 2012

26.1 Reference

Fraundorfer, F., Heng, L., Honegger, D., Lee, G. H., Meier, L., Tanskanen, P., & Pollefeys, M. (2012, October). Vision-based autonomous mapping and exploration using a quadrotor MAV. In Intelligent Robots and Systems, IROS 2012. IEEE/RSJ International Conference on (pp. 4557-4564).

26.2 Abstract

In this paper, we describe our autonomous vision-based quadrotor MAV system which maps and explores unknown environments. All algorithms necessary for autonomous mapping and exploration run on-board the MAV. Using a front-looking stereo camera as the main exteroceptive sensor, our quadrotor achieves these capabilities with both the Vector Field Histogram+ (VFH+) algorithm for local navigation, and the frontier-based exploration algorithm. In addition, we implement the Bug algorithm for autonomous wall-following which could optionally be selected as the substitute exploration algorithm in sparse environments where the frontier-based exploration under-performs. We incrementally build a 3D global occupancy map on-board the MAV. The map is used by the VFH+ and frontier-based exploration in dense environments, and the Bug algorithm for wall-following in sparse environments. During the exploration phase, images from the front-looking camera are transmitted over Wi-Fi to the ground station. These images are input to a large-scale visual SLAM process running off-board on the ground station. SLAM is carried out with pose-graph optimization and loop closure detection using a vocabulary tree. We improve the robustness of the pose estimation by fusing optical flow and visual odometry. Optical flow data is provided by a customized downward-looking camera integrated with a microcontroller while visual odometry measurements are derived from the front-looking stereo camera. We verify our approaches with experimental results.

26.3 Summary

Fraundorfer, et al. present a vision based approach for autonomous mapping and exploration using a drone. The system works mainly from stereo vision from two front faced cameras and a custom downward facing camera. An IMU and an ultrasonic sensor is also present to aid in pose and altitude estimation. Similar work includes drones using laser range finder, but consume too much power. Other approaches lack autonomy. The Quadrotor can operate in two mode: frontier based exploration and bug wall follower.

Visual odometry used, differs from conventional frame to frame matching. Instead, a reference frame is used and compared to current frames because it is not as susceptible to drift. Pose estimation is aided by optical flow camera, ultrasonic sensor, and IMU readings. Occupancy grid map is generated from stereo vision readings which is the used to generate frontiers. Closest frontier is selected by planner for autonomous exploration.

If frontier based exploration is not being accurate in current environment, it can switch to bug algorithm for wall following. Visual SLAM is present in off-board computer that allows for smooth trajectory following, loop closure detection and re-localization. Re-localization is best used when a pre-built map is present.

Results for indoor testing showed that quadrotor can explore a 30 m long corridor. Outdoor testing results are not present in this paper but a link is added, thought, not accessible as of February 2017. Visual SLAM is accurate using loop closure and re-localization.

26.4 Notes

- Autonomous vision mapping and exploration for for quadrotor drone.
- Local navigation with Vector Field Histogram.
- Frontier based exploration.
- Wall following in sparse environments.
- Ocuppancy map used by wall follower and frontier exploration.
- Images transmitter by wifi to grounded computer.
- Improved positioning with optical flow and VO.
- Quadrotor MAV ideal for reconnaissance and surveillance because of small size and GPS denied environments.
- Similar work use different sensors like laser range finders, artificial markers, vicon motion.
- Laser range require high power consumption.
- Quadrotor uses a front facing camera for mapping and navigation and a custom downward facing camera to improve algorithm.
- Bachrach et al. and Shen et al. (multifloor) implements similar work using lase scan matching.
- Eberli et al. and Meier et al. (improved) show work using waypoint markers but lack complete autonomy.
- Heng et al. implemented mapping, planning and obstacle avoidance, but with restricted autonomy.
- Bills et al. implemented high level navigation but without metric map.
- Quadrotor weights 1.4 kg, 0.6 m diameter, and 600 g payload.
- Two Matrix Vision mvBlueFOX front facing cameras.
- customized measurement and autopilot unit is also coupled to quadrotor, as well as ultrasonic distance sensor.
- x and y velocities estimated with Kalman filter. Pitch and roll taken from IMU readings.
- Altitude measured with ultrasonic sensor.
- Localization by comparing reference fram with subsequent frames.
- VO steps:
  - Extract and match FAST corners and BRIEF descriptors from left reference and current frame.
  - 3D points computed from depth map of reference frame.
  - Get 3D correspondences of current frame to references frame.
  - Compute pose with RANSAC PnP, then linear refinement.
- Mapping algorithm is used to generate 3D occupancy grid map.
- Frontier based exploration built on top of VO and mapping.
- Waypoints essentially make it active mapping.
- Exploration:

  - Extract 2D slice of the 3D occupancy grid map based on fixed altitude.
  - Occupancy map is either free, occupied or unknown.
  - Frontiers labeled next to unknown cells.
  - Frontier cells are clustered.
  - Closest frontier centroid is selected in planner.

- Wall follower use Bug algorithm.
- Walls taken from 3D points from stereo camera doing plane fitting.
- Local planning work only on frontier based exploration.
- Planner reads occupancy map and create a histogram.
- Histogram sectors are weighted to yield vector directions for smooth trajectory.
- Off board Visual SLAM constraints nodes that represent position at time t.
- Edges of graph represent constraints between poses.
- Loop detection is done with vocabulary tree approach.
- Relocalization added is pre-built map is available.
- Autonomously explores 30 m long corridor.
- Outdoor results is not included in paper. Link is added but does not work.
- Visual SLAM is accurate with loop closure constraint taken into account.
- Relocalization is close to Vicon ground truth.

26.5 Evaluation

Fraundorfer, et al. present an approach for vision based autonomous mapping and exploration with good results. They improve similar work done by other authors that use different kind of sensors. Their system works accurately for indoor and outdoor exploration. The only issue is that the link provided to access outdoor testing results was not accessible.

The paper gives a good overview of the main elements of the system. It is also very well structured. I consider this paper relevant for low cost robotics, because they rely on stereo cameras for simultaneous mapping and navigation. The approach of using cameras brings the overall cost of the system down because of the large array of alternatives for low cost cameras.

27 A Kinect-based system for physical rehabilitation: A pilot study for young adults with motor disabilities. Chang, Chen, Huang. 2011

27.1 Reference

Chang, Y. J., Chen, S. F., & Huang, J. D. (2011). A Kinect-based system for physical rehabilitation: A pilot study for young adults with motor disabilities. Research in developmental disabilities, (Vol. 32, Issue 6, pp. 2566-2570).

27.2 Abstract

This study assessed the possibility of rehabilitating two young adults with motor impairments using a Kinect-based system in a public school setting. This study was carried out according to an ABAB sequence in which A represented the baseline and B represented intervention phases. Data showed that the two participants significantly increased their motivation for physical rehabilitation, thus improving exercise performance during the intervention phases. Practical and developmental implications of the findings are discussed.

27.3 Summary

Chang, et al. present a system that uses a Kinect sensor for gesture recognition and apply it for physical rehabilitation of motor impaired patients. This paper brings the importance of promoting ways to help rehab patients without the need of a personal therapist to reduce cost and strain on patient, as well as increase motivation to perform exercises.

Other similar studies indicate that motion based games are suitable for increasing motivation and provide feedback of activities. These have a disadvantage that motion sensors need to be attached/hold in limb, which can be inconvenient for motor patients. Kinect based rehabilitation, uses the incorporated camera and depth sensor to detect the users joint position and determine if posture is correct for the specific exercise performed. Kinect also enables user to control or interact with game/software to control or regulate as needed. The system has an added advantage that it can provide feedback through a display or audio.

The system was tested with two participant presenting motor disabilities. Test was divided in two phases: baseline phase and intervention phase. Baseline phase consisted on therapist instructing the participant with rehabilitation program. Intervention phase included Kinect system.

Results compared the number of correct movement from the two phases. In general, Intervention phases provided better results due to the visual feedback available in display that showed if movement was correct.

27.4 Notes

- People with motor disabilities experience motivation loss.
- Rehabilitation requires personal assistance of a therapist, which can be expensive and time consuming.
- Only indicates approximately 30% of people perform recommended exercises. (Shaughnessy, et al. 2006)
- Kleim, et al. 2003 suggest occupational therapy can stimulate brain for better motor control.
- Strategies involving using motion based games to motivate people in engage in exercises.
- This study focuses on Kinect based rehabilitation in public school setting.

- Kinect comes with camera and depth sensor.
- Gesture recognition is applied with Kinect to determine if exercise is correctly performed.
- Two participants with motor disabilities tested the system.
- Testing using two phases: baseline and intervention phase.
- Baseline phase does not use assistive technology.
- Intervention phased used Kinerehab system.
- Results show that feedback from Kinect sensor increases the number of correct exercise moves significantly.

27.5 Evaluation

The paper presented by Chang, et al. showed good results for their test, but there is no mention on what constitutes a good posture, and the accuracy of the system itself. It only compares the number of good postures obtained from only orally instructed postures to Kinect instructed postures. The paper only shows that feedback from Kinect system is helpful for achieving correct posture/movement. There is not much information regarding the system itself.

I still consider this paper relevant to low cost robotics, because the Kinect is a relatively cheap sensor (depending on application) of good quality.

28 A robust, low-cost and low-noise artificial skin for human-friendly robots. Ulmen, Cutkosky. 2010

28.1 Reference

Ulmen, J., & Cutkosky, M. (2010, May). A robust, low-cost and low-noise artificial skin for human-friendly robots. In Robotics and Automation, ICRA 2010. IEEE International Conference on (pp. 4836-4841).

28.2 Abstract

As robots and humans move towards sharing the same environment, the need for safety in robotic systems is of growing importance. Towards this goal of human-friendly robotics, a robust, low-cost, low-noise capacitive force sensing array is presented with application as a whole body artificial skin covering. This highly scalable design provides excellent noise immunity, low-hysteresis, and has the potential to be made flexible and formable. Noise immunity is accomplished through the use of shielding and local sensor processing. A small and low-cost multivibrator circuit is replicated locally at each taxel, minimizing stray capacitance and noise coupling. Each circuit has a digital pulse train output, which allows robust signal transmission in noisy electrical environments. Wire count is minimized through serial or row-column addressing schemes, and the use of an open-drain output on each taxel allows hundreds of sensors to require only a single output wire. With a small set of interface wires, large arrays can be scanned hundreds of times per second and dynamic response remains flat over a broad frequency range. Sensor performance is evaluated on a bench-top version of a 4 4 taxel array in quasi-static and dynamic cases.

28.3 Summary

Ulmen and Cutkosky present an artificial skin for human friendly robotis. Their design have several objectives in mind: it should be low cost, can withstand unexpected collisions, scalable, low noise, adaptable, and lightweight with low power consumption. Previous work meet some of the requirements at the expense of others such as cost and scalability.

They explore several types of sensor suited for this task and evaluate capacitive sensors is the best choice because those are non-contact and can take any shape. Components required to build each taxel can be obtained for 0.10 USD. The skin is divided in several layers. Three capacitive layers are needed, where outer layers protect inner layer from wear and noise. A silicone foam separates each capacitive layer. A small multi-vibrator circuit measures capacitance.

The design allows for thousand of taxels to connect to a single wire, preventing interconnections. Since only one sensor can be active, scanning is necessary to achieve near simultaneous readings. With the proposed design, high sensor density can be achieved (10 per cm^2).

Since sensor is constructed in layers, stiffness is nonlinear. Calibration is needed to linearize data. Testing showed skin sensitivity ranging from 0 to 100 N force.

Future work involves exploring designs for larger array of sensors in flexible form. Proximity detection is also planned.

28.4 Notes

- Human interaction increases the need human friendly robots.
- Human friendly skin for robots to provide force sensing.
- Objectives:
  - Energy absorbing, and durable to mitigate unexpected collisions.

  - Scalable with few wires.
  - Low cost.
  - Low noise and low hysteresis.
  - Adaptable to curved surface.
  - Lightweight, low power.

- Similar artificial skins have excellent energy absorption, but lack dynamic response. Others, are scalable but do not completely cover robot. Others are fully scalable but are costly.
- Several types of sensors have be explored, such as: piezoelectric, piezoresistive, optical, force-sensing resistors, quantum tunneling composite and capacitive.
- Capacitive is used because it is non contact, can be made into any shape and is sufficiently flexible.
- Noise can be mitigated with good design.
- High resiliency closed cell silicone foam from McMaster-Carr is used as dielectric layer.
- Three layered capacitive force sensor with outer layers protecting the inner layer.
- Multivibrator circuit is inexpensive to build.
- Components for each taxel costs 0.10 USD.
- Thousands of sensors can be connected to a single output wire.
- Single wire minimize connections.
- 2 n wires for n x n grid sensor array.
- Only one sensor active at a time.
- Fast scanning allow for near simultaneous readings. Advantage: only logic and clock wires needed.
- Single NAND gate required for each sensor.
- 100 sensors scanned at 1 kHz.
- 10 sensors per cm^2 is easily achievable.
- Foam layers cause nonlinear stiffness, calibration is needed.
- Measurements are repeatable.
- Read from 0 to 100 N force.
- Future work include exploring proximity sensor, and design larger arrays in flexible form.

28.5 Evaluation

The paper presented by Ulmen and Cutkosky is relevant to low cost robotics, because as implied by the authors, humans interacting with robots is becoming more common. The robotics skin presented is a low cost sensor that can cover human friendly robots and provide feedback as well as safety (from contact).

Their described artificial skin shows good results and is sensible enough that it can detect small forces. The only issue is that accuracy is not mentioned, only repeatability. If this sensor is accurate, then this can be a good choice for human friendly robot skin.

29 Accurate odometry and error modelling for a mobile robot. Chong, Kleeman. 1997

29.1 Reference

Chong, K. S., & Kleeman, L. (1997, April). Accurate odometry and error modelling for a mobile robot. In Robotics and Automation, ICRA 1997. IEEE International Conference on (Vol. 4, pp. 2783-2788).

29.2 Abstract

This paper presents the key steps involved in the design, calibration and error modelling of a low cost odometry system capable of achieving high accuracy dead-reckoning. A consistent error model for estimating position and orientation errors has been developed. Previous work on propagating odometry error covariance relies on incrementally updating the covariance matrix in small time steps. The approach taken here sums the noise theoretically over the entire path length to produce simple closed form expressions, allowing efficient covariance matrix updating after the completion of path segments. Systematic errors due to wheel radius and wheel base measurement were first calibrated with UMBmark test. Experimental results show that, despite its low cost, our system's performance, with regard to dead-reckoning accuracy, is comparable to some of the best reported odometry vehicle.

29.3 Summary

Chong and Kleeman present an algorithm to accurately calculate a robot position using wheel odometry and how to model errors in the motors. They describe the steps to design, calibrate, and model errors for a low cost odometry system. Authors compare previous work, but find it inconsistent because they do not correctly model error propagation or make assumptions such as circular error (Leenhouts, 1985).

Their design consist of a differential drive robot. The calibration step consists of running a path n times and use offsets as tunning factor for equations. In their approach, decompose path traveled into a series of three type of motions: straight line, circular, and arc motion. Path can be decomposed into small k steps, where variance in each travel unit is proportional to distance traveled. Covariance propagation is done k times.

Robot was tested by comparing odometry estimate with sonar reading taken as ground truth. Results showed confidence of 95%.

29.4 Notes

- Key steps involved in design, calibration and error modeling of low cost odometry system.
- Can achieve high accuracy dead-reckoning.
- Odometric localization accumulates error over time.
- Gyroscopes and accelerometers is susceptible to drift.
- Odometry error can be systematic or non-systematic.
- Systematic error can be identified as difference in wheel diameter or effectiveness of wheel base.
- Non-systematic error lack consistency.
- Classical models which assume error in previous stage is not correlated with error introduced by input can not deal with non systematic error.

- Other work is also inconsistent because error propagation dealt in multiple parts yield different results.
- Others, such as circular error probable, assumes equal error in all directions.
- Path can be decomposed into series of three types of motion: circular, straight line, and arc motion.
- Design and assumptions:
  - Motor in each wheel.
  - Error for each small travel is zero mean.
  - Variance of each travel unit is proportional to distance traveled.
- Calibration: robot travels a path n times and offsets are used as tuning factors.
- Error model:
  - Entire path divided into small k segments.
  - Covariance of error propagation is done k times.
  - Constant speed at infinitesimal k.
  - Remove need to incrementally update covariance matrix for circular motion.
  - Straight line and arc limit k.
- Testing robot using sonar array to compare estimate to actual state.
- Robot tested by moving 10 m forward and then backwards (60 trials), then comparing odometry estimation with actual state.
- Result show confidence of 95%.

29.5 Evaluation

The paper presented by Chong and Kleeman is relevant to both robotics in general and low cost robotics because wheel odometry is present in several other algorithms such as Kalman filter and particle filter. Error modeling is an aspect that low cost robotics need to deal with because of the errors that come with using low cost sensors, actuators and materials.

30 Kilobot: A low cost scalable robot system for collective behaviors. Rubenstein, Ahler, Nagpal. 2012

30.1 Reference

Rubenstein, M., Ahler, C., & Nagpal, R. (2012, May). Kilobot: A low cost scalable robot system for collective behaviors. In Robotics and Automation, ICRA 2012. IEEE International Conference on (pp. 3293-3298).

30.2 Abstract

In current robotics research there is a vast body of work on algorithms and control methods for groups of decentralized cooperating robots, called a swarm or collective. These algorithms are generally meant to control collectives of hundreds or even thousands of robots; however, for reasons of cost, time, or complexity, they are generally validated in simulation only, or on a group of a few tens of robots. To address this issue, this paper presents Kilobot, a low-cost robot designed to make testing collective algorithms on hundreds or thousands of robots accessible to robotics researchers. To enable the possibility of large Kilobot collectives where the number of robots is an order of magnitude larger than the largest that exist today, each robot is made with only $14 worth of parts and takes 5 minutes to assemble. Furthermore, the robot design allows a single user to easily operate a large Kilobot collective, such as programming, powering on, and charging all robots, which would be difficult or impossible to do with many existing robotic systems.

30.3 Summary

Rubenstein, et al. present a low cost robot that can be used to test collective algorithms. Authors mention there is considerable work to develop algorithms for collective robotics, but are usually simulated. They explore similar work and find it is expensive or requited complex operation. Some also lack scalability.

Kilobot uses a vibrating motor for locomotion, and is able to move in straight line, and rotate on both directions. To communicate with nearby robots, infrared light is emitted downwards. Reflected light is detected by nearby robot. Light intensity is measured to calculate distance up to 10 cm. All components to built robot cost approximately 14 USD, and can be assembled in 5 minutes.

In active state, it can last from 3 to 24 hours depending on power consumption. To enable scalability, Kilobot can power down for 1 minute and turn on to sense if there is a message, if not it powers down again. Cycle can last 3 months. Charging can be done by connecting legs and battery input on top to 6 Vdc. Programs can be sent by messages through infrared.

Path following and orbiting was demonstrated possible and with good performance. A single robot cannot does it by itself, it needs to communicate with other robots that function as markers.

30.4 Notes

- Low cost robot to test collective algorithms.
- There is a lot of algorithms developed for robotic collectives, but everything is simulated.
- Difficult to accurately model robots for simulation.
- Simulation may hide problems for large number collectives.
- Similar work only limited to a number of robots, high cost, and complex operation.
- Robot must act as a whole and not require individual attention. (scalable)
- Examples of scalability: charging, send program wirelessly.

- Parts cost 14 USD.
- 5 minute assembly.
- Vibration based locomotion.
- Range only sensor.
- Based on SDASH.
- Requirements:
  - move forward.
  - rotate.
  - communicate with neighbors,
  - measure distance to neighbor
  - have sufficient memory to run SDASH.
- Additionally should measure ambient light and display internal state to assist debugging.
- Slip-stick principle for vibration locomotion.
- Can go forward, turn clockwise and anticlockwise.
- Cannot move over rough terrain.
- Communication via infrared transmitter and receiver at bottom of Kilobot.
- Allow for transmission in all direction.
- Messages relayed by pulsing transmitter.
- Communication rate of 30 kb/s to robots at 10 cm away. (all robots use same channel)
- CSMA/CA to avoid two robots transmitting at the same time.
- Light intensity is measured to estimate distance to transmitter.
- Measured distance of +/- 2 mm accuracy and 1 mm precision.
- Visible light sensor included but not used.
- Two speeds for vibrating motors.
- Power robot for 3 to 24 hours.
- Orbit and path following demonstration. (need other robots as markers)
- Kilobots powers down for 1 minute and turns on to check for messages for 10 s.
- Can repeat this cycle for 3 months on single battery charge.
- Charging by connecting legs and battery input on top to 6 Vdc.
- Programs are sent over infrared messages.
- RGB LED to display battery.

30.5 Evaluation

Rubenstein, et al. bring a low cost solution to test collective behavior since related work is usually done in simulation. Kilobot fulfills all typical requirement necessary for collective robots using low cost components while showing good results. This robot is suitable for collective behavior, albeit with some limitations.

Depending on application, some of the drawbacks can be the short active time of the robots, as 24 hours may not be sufficient for monitoring. It also lacks odometry for localization. Kilobot can sense nearby robots, but it is not able to localize itself. Also, vibration locomotion is not suitable for rough and uneven terrain.