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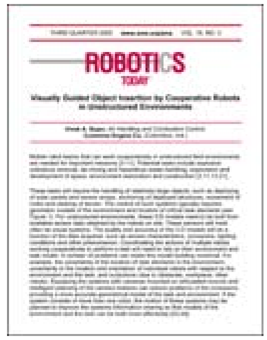

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6D SLAM with Kurt 3D

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Automatic environment sensing and modeling is a fundamental scientific issue in robotics because the presence of maps is essential for many robot tasks. Manual mapping of environments is a hard and tedious job. Thrun et al. report a time of about one week of hard work for creating a map of the museum in Bonn for the robot RHINO [9]. This is especially true for mobile systems with 3-D laser scanners that automatically perform multiple steps, such as scanning, gaging and autonomous driving, because they have the potential to greatly improve mapping. Many application areas benefit from 3-D maps, such as industrial automation, architecture, agriculture, the construction or maintenance of tunnels and mines and rescue robotic systems.

The robotic mapping problem is that of acquiring a spatial model of a robot's environment. If the robot poses were known, the local sensor inputs of the robot, such as local maps, could be registered into a common coordinate system to create a map. Unfortunately, any mobile robot's self-localization suffers from imprecision and therefore the structure of the local maps, for example, of single scans, needs to be used to create a precise global map. Finally, robot poses in natural outdoor environments necessarily involve yaw, pitch, roll angles and elevation, turning pose estimation as well as scan registration into a problem with six mathematical dimensions.

State of the Art

State of the art for metric maps are probabilistic methods, where the robot has probabilistic motion models and uncertain perception models. Through integration of these two distributions with a Bayes filter, such as Kalmanor particle filter, it is possible to localize the robot. Mapping is often an extension to this estimation problem. Beside the robot pose, positions of landmarks are estimated. Closed loops, for example, a second encounter of a previously visited area of the environment, play a special role here: once detected, they enable the algorithms to bound the error by deforming the mapped area to yield a topologically consistent model. However, there is no guarantee for a correct model. Several strategies exist for solving simultaneous localization and mapping (SLAM). Thrun surveys existing techniques, such as maximum likelihood estimation, expectation maximization, extended Kalman filter or (sparsely extended) information filter SLAM [10].

SLAM in well-defined, planar indoor environments is considered solved, but 6D SLAM still poses a challenge because several strategies become infeasible, for example, with six degrees of freedom, the matrices in Kalman or information filter SLAM grow more rapidly and a multihypothesis approach would require too many particles. Therefore, 3-D mapping systems [2-4,6,7] often rely on scan matching approaches.

Kurt 3D

Three-Dimensional Laser Range Finder. The 3-D laser range finder (*Figure 1*) [7] is built on the basis of a SICK 2-D range finder by extension with a mount and a small servomotor. The 2-D laser range finder is attached in the center of rotation to the mount for achieving a controlled pitch motion with a standard servo.

The area of up to 180 (h) ×120 (v) is scanned with different horizontal (181,361,721) and vertical (128,256,400,500) resolutions. A plane with 181 data points is scanned in 13 ms by the 2-D laser range finder (rotating mirror device).

Planes with more data points, such as 361,721, duplicate or quadruplicate this time. Thus a scan with 181 × 256 data points needs 3.4 sec. Scanning the environment with a mobile robot is done in a stop-scan-go fashion.

Mobile Robot. Kurt 3D (*Figure 1*) is a 45 x 33 x 29 cm mobile robot that weighs 22.6 kg. Two 90 W motors are used to power the six-skid-steered wheels, whereas the front and rear wheels have no read pattern to enhance rotating. The core of the robot is a Pentium-Centrino-1400 with 768 MB RAM and Linux.

Figure 1. *Kurt 3D.*

6D SLAM

To create a correct and consistent environment map, 3-D scans have to be merged into one coordinate system. This process is called registration. If the robot carrying the 3-D scanner were localized precisely, the registration could be done directly based on the robot pose. However, due to the imprecise robot sensors, self-localization is erroneous, so the geometric structure of overlapping 3-D scans has to be considered for registration. As a byproduct, successful registration of 3-D scans relocalizes the robot in 6-D by providing the transformation to be applied to the robot pose estimation at the recent scan point.

Kurt 3D's SLAM algorithm consists of four steps, which are explained in the following subsections.

Odometry Extrapolation. The odometry is extrapolated to six degrees of freedom using previous registration matrices, for example, the change of the robot pose $\Delta\mathbf{P}$ given the odometry information $(x_n, z_n, \theta_{y,n})$, $(x_{n+1}, z_{n+1}, \theta_{y,n+1})$ and the registration matrix $\mathbf{R}(\theta_{x,n}, \theta_{y,n}, \theta_{z,n})$ is calculated by solving:

$$\begin{pmatrix} x_{n+1} \\ 0 \\ z_{n+1} \\ 0 \\ \theta_{y,n+1} \\ 0 \end{pmatrix} = \begin{pmatrix} x_n \\ 0 \\ z_n \\ 0 \\ \theta_{y,n} \\ 0 \end{pmatrix} + \left(\begin{array}{c|c} \mathbf{R}(\theta_{x,n}, \theta_{y,n}, \theta_{z,n}) & 0 \\ \hline 0 & \begin{matrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{matrix} \end{array} \right) \cdot \underbrace{\begin{pmatrix} \Delta x_{n+1} \\ \Delta y_{n+1} \\ \Delta z_{n+1} \\ \Delta\theta_{x,n+1} \\ \Delta\theta_{y,n+1} \\ \Delta\theta_{z,n+1} \end{pmatrix}}_{\Delta\mathbf{P}}.$$

Calculating Heuristic Initial Estimations for ICP Scan Matching. For the given two sets *M* and *D* of 3-D scan points stemming from the 3-D scans, the heuristic computes two octrees based on these point clouds (*Figure 2*). The octrees rigid transformations are applied to the second octree, until the number of overlapping cubes has reached its maximum. The transformations are computed in nested loops. However, the computational complexity is reduced due to the fact that the search is limited to space relative to the octree cube size. Details can be found in Ref. [4].

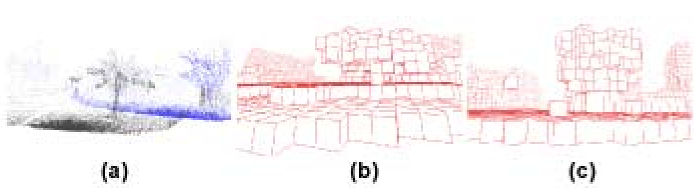

Figure 2. *(a) Two 3-D point clouds, (b) octree corresponding to the black point cloud and (c) octree based on the blue points.*

Scan Registration. Well-known iterative closest points (ICP) algorithms are used to calculate a rough approximation of the transformation while the robot is acquiring the 3-D scans [1]. The ICP algorithm iteratively calculates the point correspondence.

In each iteration step, the algorithm selects the closest points as correspondences and calculates the transformation (**R**, **t**) for minimizing the equation:

$$E(\mathbf{R}, \mathbf{t}) = \sum_{i=1}^{N_m} \sum_{j=1}^{N_d} w_{i,j} \left|\left|\mathbf{m}_i - (\mathbf{R}\mathbf{d}_j + \mathbf{t})\right|\right|^2, \qquad (1)$$

where N_m and N_d are the number of points in the model set *M* or data set *D*, respectively, and w_{ji} are the weights for a point match. The weights are assigned as follows: w_{ji} =1, if $\mathbf{m}_i$ is the closest point to $\mathbf{d}_j$ within a close limit, w_{ji} = 0 otherwise. The assumption is that in the last iteration step, the point correspondences, thus the vector of point pairs are correct.

Loop Closing. After matching multiple 3-D scans, errors have accumulated and loops would normally not be closed. The algorithm automatically detects a to-be-closed loop by registering the last acquired 3-D scan with earlier acquired scans. A hypothesis based on the maximum laser range and on the robot pose is therefore created so that the algorithm does not need to process all previous scans. The octree-based method is then used to revise the hypothesis. Finally, if a registration is possible, the computed error, for example, the transformation (**R**, **t**), is distributed over all 3-D scans.

Model Refinement. Based on Pulli approach, the relaxation method of simultaneous matching was designed [7]. The first scan—masterscan—determines the coordinate system, which is fixed. The following three steps register all scans and minimize the global error, after a queue is initialized with the first scan of the closed loop:

1. Pop the first 3-D scan from the queue as the current one.
2. If the current scan is not the master scan, then a set of neighbors (set of all scans that overlap with the current scan) is calculated. This set of neighbors forms one point set *M*. The current scan forms the data point set *D* and is aligned with the ICP algorithms. One scan overlaps with another if more than *p* corresponding point pairs exist. In this implementation, *p* = 250.
3. If the current scan changes its location by applying the transformation (translation or rotation) in step 2, then each single scan of the set of neighbors that is not in the queue is added to the end of the queue. If the queue is empty, terminate; else continue at step 1.

In contrast to Pulli's approach, this method is totally automatic and no interactive pairwise alignment has to be done. Furthermore, the point pairs are not fixed [5]. The accumulated alignment error is spread over the whole set of acquired 3-D scans. This diffuses the alignment error equally over the set of 3-D scans [8].

Conclusion

The proposed methods have been tested on various data sets, including test runs at RoboCup Rescue and ELROB. *Figure 3* show two closed loops. Three-dimensional animations of the scenes can be found at **http://kos.informatik.uni-osnabrueck.de/download/6Dpre** and **http://kos.informatik.uni-osnabrueck.de/download/6Doutdoor/**. The loop in the left part of *Figure 3* was closed manually, whereas the right loop was detached automatically.

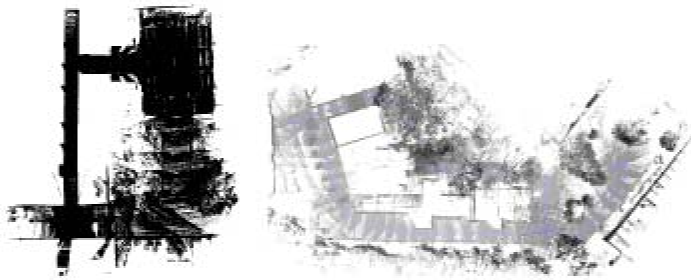

Figure 3. *(a) Two 3-D point clouds in top view, (b) closed loop with nine million 3-D data points and (c) loop with seven million points and a path length of over 250 m.*

These large loops require reliable robot control architecture for driving the robot and efficient 3-D data handling and storage methods. In future work, the emerging topic of map management will be tackled.

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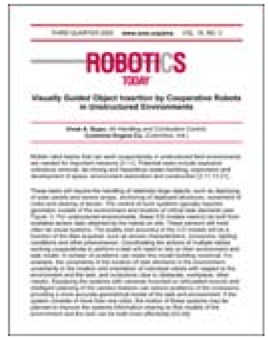
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Visually Guided Object Insertion by Cooperative Robots in Unstructured Environments

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New Cell Control System

The HOST Cell Control System (CCS) redefines how testing is performed in automotive laboratories. It leverages the latest hardware and software technology to provide users with a cost-effective state-of-the-art test cell management tool. At the heart of the system is the single computer test CCS. The foundation for this mission-critical computer consists of a fan-less processor, compact flash storage, DiskOnChip® and a real-time operating system. This enables the system to meet the demanding testing needs while eliminating the three most common hardware failures: processor overheating, hard drive failure and virus susceptibility. The software has been highly optimized to control the dynamometer, fan, robot (throttle or throttle and brake actuator) and data acquisition. The HOST is compatible with any dynamometer system, even if it is not a **Burke Porter** (Grand Rapid, Mich.) machine. Therefore, providing a cost-effective and flexible solution that also drives down maintenance costs and increases uptime.

Servo Gun Training Now Offered

Applied Manufacturing Technologies Inc. (Orion, Mich.) is now offering a new servo gun training class for engineers and manufacturing skilled trades. The new class, which is offered at the customer's site, focuses on servodriven spot-welding guns for robotic applications and will be valuable to automotive OEMs and other part manufacturers that have spot welding robots with servoweld guns. The classes will consist of either servo gun training for Fanuc RJ3iB robots or ABB IRC5 robots. Servo guns offer better weld quality, faster cycle times and longer weld tip life. The weld gun is controlled more precisely by a servodriven motor as opposed to the older method of being controlled by a pneumatic cylinder. AMT is one of a few companies that offer the knowledge and expertise to do servo gun training.

Stainless Steel Robot

KUKA Robotics Corp. (Clinton Township, Mich.) has been selected by **Zepnick Solutions Inc.** (Green Bay, Wisc.) as its robotics supplier for its new food handling system. Zepnick has incorporated the KUKA KR 15 SL stainless steel robot into its food handling and packaging system, which will allow manufacturers to increase production and improve working conditions. The use of stainless steel on all the robot's surfaces, together with the high IP rating, makes the KUKA KR 15 SL robot suitable for all fields of application with stringent requirements as to hygiene, sterility and absence of particles, including the food, pharmaceutical, medical and beverage industries. The KUKA KR 15 SL is a six-axis robot with a 1,503 mm reach and capable of handling up to 15 kg payload. The new packaging system utilizes a vision system to determine the coordinates of randomly placed product on a moving conveyor, and these coordinates are then transferred to the robot. Utilizing the robot's conveyor tracking software, it then tracks the position of the product. The robot picks the product off the moving conveyor and places the product into a wrapper or carton.

Digital Servodrive

Available in three models, the Didge provides up to 6 amps of continuous output power and 12 amps of peak power in a metal, nonventilated industrial assembly. **Elmo Motion Control's** (Westford, Mass.) Didge operates in current, velocity, position or advanced position modes for AC/DC brushless or brush motors, linear motors or voice coils. Additionally, it operates in trapezoidal or sinusoidal communication with vector control as a standalone unit or as part of a distributed multiaxis system in a real-time network. Elmo's Didge offers OEMs a highly cost-effective solution. In addition to a wide variety of features, the Didge can be easily set up and tuned. Users can also use Elmo's Composer software suite for rapid drive configuration for optimized integration of the motor. The Didge does not require additional modules for feedbacks and filters to comply with EMV standards. As part of Elmo's SimplIQ family, the Didge features a wide variety of feedback options, including incremental encoder, hall sensor, tachometer, potentiometer, resolver and interpolated SIN/COS encoder. It also contains the same firmware as the other SIMPIIQ digital drives and is, therefore, compatible with all of Elmo's existing, comprehensive tools.

New High-Precision Piezo-Driven Stage

A new high-precision linear stage model, MT 84-25-PM, is now available from **Steinmeyer Inc.** (Burlington, Mass.). This table features a sleek low-profile design with an overall width of only 27.5 mm and length of 84 mm with a standard travel of 25 mm. Manufactured from high-strength anodized aluminum, the table weighs just 600 g and offers resolutions down to 5 nm and repeatability of ±10 nm. Included inside this impressive, compact design are a piezo linear motor with incremental linear encoder and preloaded cross roller bearings. The MT 84-25-PM stage can be manufactured for cleanroom, high vacuum and nonmagnetic applications upon request and is an excellent choice for nanotechnology, metrology, biomedical miniature robotics and medical industry applications.

New Class 1 Clean Room Six-Axis Robots

Adept Technology (Livermore, Calif.) has released its new Adept Viper™ s650 and s850 Class 1 cleanroom robots, expanding the range of robotic applications available to customers in the solar, disk drive, LCD, semiconductor and life sciences markets. The robots bring high performance, precision motion and full six-axis dexterity to cleanroom assembly, handling, testing and packaging applications. Both robots run on Adept's industry-leading SmartController™ CS controls and software platform, providing superior path following, faster cycle times, better repeatability, integrated vision and embedded networking. The Adept Viper s650CR and s850CR robots are backed by a two-year warranty and Adept's award-winning 24/7 global service organization.

Pneumatic Lift Degater Handles Plastic Parts

The new Lift Degater from **SAS Automation** (Xenia, Ohio) provides injection molders with additional downstream automation. This new Lift Degater was designed for large plastic parts. A robot transports the part to the SAS Lift Degater and sets the part into the "part conforming nests," located at the top of the Degater. The part is then trimmed by several precisely positioning cutting tools that match to the nests. Precision and speed are coupled with several simultaneous cutting actions. The waste trim is dropped directly into a container, and the finished molded part is lowered on the lift table to be removed by a packer. The packer is protected from the lift by a safety light curtain. SAS produces custom degaters using lift tables, rotary tables and stationary cutting presses depending on the specific application. Most systems, similar to the lift table described above, are operated pneumatically. Secondary automation is important to any robotic cells. As a specialist in robotic end-of-arm tooling, SAS has the automation expertise to take the part from the mold and continue its movement until its final destination. SAS is experienced in both automatic insert-molding applications, runner separation and automatic post-mold degating equipment for a wide variety of part shapes and weights.

Automated Turning Center

Changing parts with a loading/unloading time of less than 5 sec., **Fuji's** (Vernon Hills, Ill.) new FS4-3500 compact automated turning center with four-position turret is the fastest in its class. Ideal for large production runs, this machine allows loading and unloading of the workpiece during spindle rotation. Two separate loaders are included for loading and unloading. The time-tested FS4-3500 is the machine of choice where uptime and speed are critical. The FS4-3500 is as precise as it is fast. It incorporates a 30° bed design. The saddle and cross slides are coated with TURCITE-type material to reduce stick slip. This proven design along with Fuji's mid-case spindle assures super high accuracy, superior roundness and finish in high-volume production environments. Fuji's automatic gauging can be integrated into extremely high-accuracy applications where 100% inspection is required. The FS4-3500 is especially suitable for bearing applications, as well as transmission parts requiring short cycle times. This incredibly accurate box-way machine with four-position turret allows for maximum metal removal required by bearing manufacturers worldwide. The FS4-series can be applied to most applications that require both OD and ID turning. The machine can be connected with a part flip station for complete OP-10/OP-20 turning.

Finishing Tool

VersaFinish™, an axially compliant finishing tool ideally suited for robotic and automated material finishing operations on aluminum, plastic, steel and so on, is available from **ATI Industrial Automation** (Apex, N.C.). The robust, low-speed, high-torque finishing tool has a unique "floating" motor and spindle arrangement that provides the finishing tip's axial compliance to perform consistently on irregular part patterns. The VeraFinish, mounted to a robot or CNC machine, has a vane-type air motor with gear reduction providing a long service life with exceptional power. Remotely adjusted air pressure controls and maintains the constant axial force on the floating spindle, allowing users to compensate for deviations in the part's profile. The axial motion of the spindle allows for fast and simple programming in robotic applications. Optional sensing devices are available to detect the spindle speed and forward and retracted spindle positions. All units have a forward sensor that detects the tools engagement with the workpiece.

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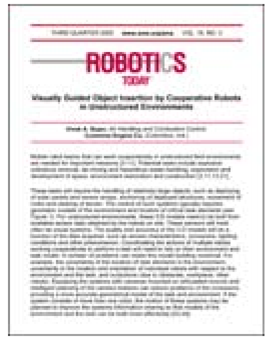

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