Bojan Jerbić
Božo Vranješ
Miljenko Hrman
Zoran Kunica

ISSN 1333-1124

INTELLIGENT ROBOTIC ASSEMBLY USING MACHINE VISION AND CAD INTEGRATION

Summary

This paper deals with the development of an autonomous robotic assembly system capable of operating in a disordered working environment. A fundamental prerequisite for the autonomous robot behavior is the perception of its environment. The machine vision has proven to be the main technology that provides the visual perception to technical systems. The model of the integrated autonomous assembly system developed in this work uses machine vision based on the idea of information integration. The given approach tends to maximize the use of the CAD data and the integration of the subsequent assembly process, i.e. the integration of engineering and process information. The CAD model embodies a description of the product geometry, which determines the parameters of the production and assembly processes, primarily applied for vision system. In accordance with the presented model, an autonomous robotic assembly cell is realized and the required machine vision software and robot control program are developed. The system is verified on real assembly tasks, by using a simple laboratory product.

Keywords: vision, robotics, assembly, automation, artificial intelligence

Sažetak

Ovaj rad prikazuje razvoj autonomnog robotskog montažnog sustava sposobnog za rad u nesređenoj radnoj okolini. Temeljni preduvjet za mogućnost autonomnog djelovanja robota je njegova percepcija okoline. Strojni vid se nametnuo kao osnovna tehnologija koja omogućuje vizualnu percepciju tehničkim sustavima. Model integriranog autonomnog montažnog sustava razvijenog u ovm radu koristi strojni vid zasnovan na principu integracije informacija. Prikazani pristup teži maksimizaciji korištenja CAD podataka i integraciji odgovarajućih montažnih procesa, tj. integraciji projektnih i procesnih informacija. CAD model sadrži opis geometrije proizvoda, koji određuje parametre proizvodniih i montažnih procesa, prvenstveno korištenih kod vizijskih sustava. U skladu s prikazanim modelom, izvedena je autonomna robotska jedinica, te je razvijena odgovarajuća programska podrška za upravljanje robotom i vizijskim sustavom. Sustav je provjeren na realnim montažnim zadaćama, koristeći jednostavan laboratorijski prototip.

Ključne riječi: *vid, robotika, montaža, automatizacija, umjetna inteligencij*a

1. Introduction

Machine vision is a technology which gives visual perception to technical systems with the aim to improve their functionality and provide autonomous working capabilities (Jain, Kasturi and Schunk 1995; Zeuch 2000). Thanks to machine vision and other related technologies, such as computer science, artificial intelligence, new materials, and nanotechnology, modern technical artifacts inherit human capabilities, tending to replace and/or complement many of our work activities (Minsky 1963; Jerbić 2002; Jerbić 1999).

This exciting technology contributes a new quality to manufacturing, particularly where industrial robots appear as widespread equipment. Using machine vision technology, robots are able to work in somewhat uncontrolled working conditions, almost like humans do.

Among different manufacturing domains, assembly appears to be one of the most demanding technologies, requiring the application of very complicated mechanical capabilities correlated by perception and intelligence. In other words, assembly technology needs working capabilities immanent in humans rather than in machines.

Generally speaking, the functionality of an automatic assembly system mostly depends on the work piece geometry. Even slight product changes require substantial alterations to the system. In addition, automatic systems usually require a completely controlled working environment. It means that positions and orientations of the parts and all system elements are precisely determined.

By using machine vision, automatic devices and robots can dynamically scan the working environment, discover changes and adapt their behavior to the actual situation. Machine vision gives a much higher degree of freedom to an automatic system, dramatically improving the flexibility and working autonomy of the system.

This paper deals with the development of a model of the robotic assembly system which is able to work in a disordered/chaotic environment. The application of machine vision whose knowledge base is generated from the CAD system is stressed. This approach defines the interfaces to the engineering work and knowledge, minimizing the information entropy. The model of a product, designed by the CAD system during the design phase, includes all information about the related geometry that vision system needs for object recognition. On the other hand, the process data (primarily assembly sequence) are required to provide a complete information frame for the intelligent control program which is then able to induce the autonomous robot operation.

2. Concept of the integrated system for automatic assembly in disordered environment

In this paper, the phrase "controlled, ordered or restrained environment" presumes a certain type of knowledge about the state of the system and the process, which comes from the perspective of working subjects. An increase in the level of information/knowledge which system elements/devices use for work means a relative increase in the level of control. If a robot is able to find out the position of a work piece which is not completely restrained in the work space, using certain perception, knowledge and intelligence, it can be said that the system is completely controlled. Therefore, the following hypothesis can be defined:

The level of control of an automatic system is proportional to the knowledge of/information about the corresponding system and process rather than the determinism of physical arrangement of their elements.

In an automatic assembly the control of a system is usually connected to the control of the working environment. Uncontrolled situation is any situation where any object or subject is not completely defined from the aspects of position, orientation, action and/or process. In order to get an automatic system controlled, the corresponding knowledge about the system and process must exist. Dynamic information control, based on the perception of the environment, needs less predetermined operational and structural knowledge.

The determinism of the work piece position and orientation is one of the most important factors which determine the control level of the automatic system working environment, and is closely related to handling operations. The handling operations denote the operations that move objects from-to required positions and orientations. The transition from the free to the controlled/known spatial state is one of the most demanding tasks in automatic processes.

By using machine vision in an automatic system, the information about the position and orientation of the work objects can be acquired dynamically during the process. In this way, the state of each object is determined, even if the objects are freely located, and consequently, the assembly system becomes controlled.

Figure 1 shows the concept of machine the vision application in an automatic system based on the above described assumptions. The idea of the described concept is based on the intention to minimize the information entropy. Therefore, the concept starts from the product design, namely, from the CAD data where the essential engineering information is created. The CAD model includes the analytical/mathematical representation of geometrical, functional and physical characteristics of a future product. That information which forms the virtual product is the source of all necessary information which helps to work out most of the subsequent engineering tasks, such as FE analysis, NC programming, mechanism/functional simulation and all other related issues. The ignoring of the generated information causes entropy in the product development and manufacturing cycle. In the described concept the CAD data are used for:

- manufacturing planning,
- assembly process planning,
- carrying out of assembly process (machine vision)

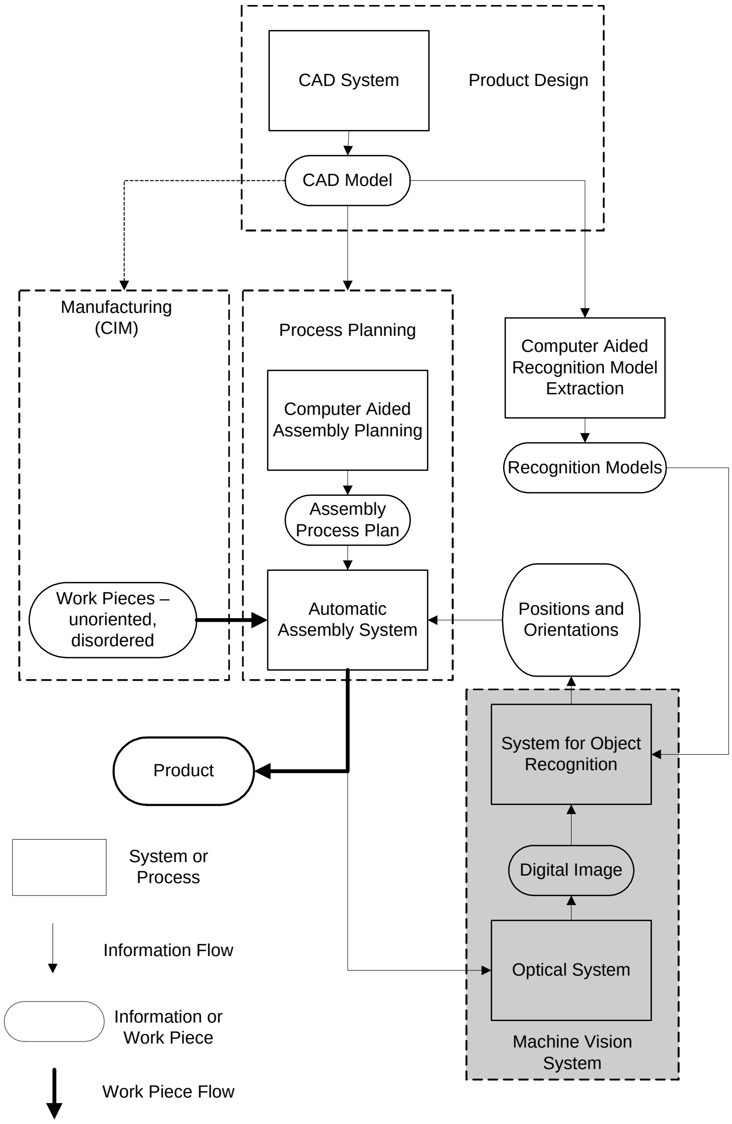

Figure 1 Concept of an integrated system for automatic assembly in disordered environment

Slika 1. Koncept integriranog sustava za automatsku montažu u nesređenoj okolini

3. Robotic assembly using machine vision

The developed robotic system for performing assembly in a disordered/uncontrolled working environment includes: a CCD digital camera, a frame grabber, a PC, a robot with a controller and corresponding control programs.

The control programs combine the machine vision and robot motion control programs. The machine vision program is developed by using the HEXSIGHT object library (Adept 2001), i.e. basic vision algorithms for filtering, segmentation, calibration, etc. The main task of the vision program is to interpret the contents of the images scanned/captured by the CCD camera. More precisely, the vision program is responsible for identifying the work pieces and finding out their position and orientation in the robot's work space.

According to the suggested concept, the automatic system must include integration components. The integration is mainly related to the CAD system and planning tools (Kunica and Vranješ 1999; Chakrabarty 1997; Jones, Wilson and Calton 1998).

The robot's control program takes over the results from the vision system and assembly planning software to define the movement plan and the pick & place locations. The program combines the processing of data on the robot controller and on the PC. They communicate over the Ethernet connection using TCP/IP and NFS protocols. The program on the PC is responsible for processing the vision system data and for transferring the results to the robot controller, where the corresponding program runs the robot.

3.1. Vision system

The base structure of the vision system program is given in Figure 2. The base structure comprises the elements that directly participate in the recognition of the work pieces and the computation of their positions and orientations. Some program routines, for example for visualization, window interface and data management, are not covered by the schema. The vision program inputs include:

- Monochromatic digital image in matrix representation, digitized from an analogue video signal
- Vectorized digital image created in the CAD system from the 3D model of the work piece
- Assembly sequence
- Homogeneous transformation which defines a coordinate system relative to the robot's base coordinate system.

The output from the vision program, i.e. the results of the image processing, contains the positions and orientations of the work pieces in the robot's work space. The coordinates are expressed relative to the robot's coordinate system, and ordered in accordance with the assembly sequence, so they can be directly applied by the robot for handling the parts.

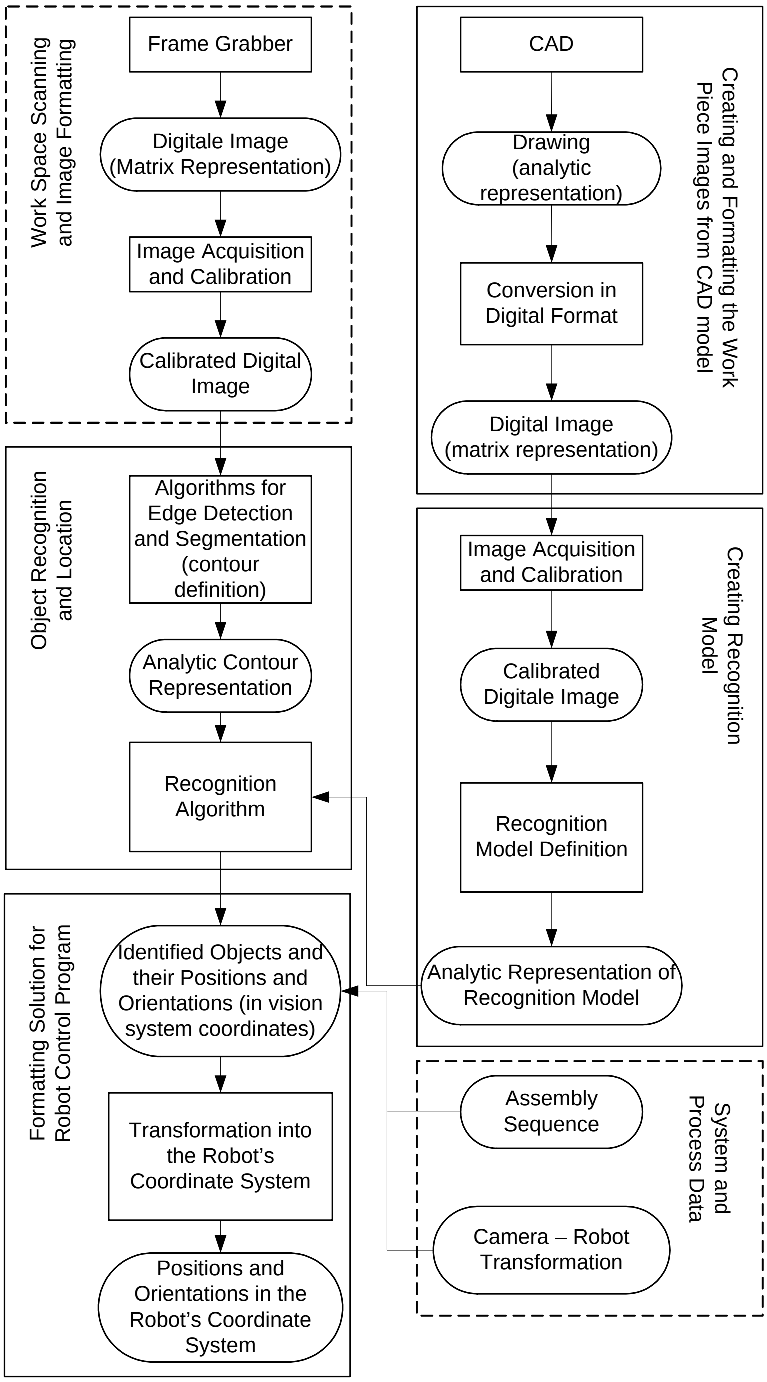

Figure 2 Configuration of the vision system software

Slika 2. Struktura softvera vizijskog sustava

3.1.1. Creating and formatting images

A digital image is created by a digitizing device. A raw digital image is not suitable for the recognition process since it is distorted due to the imperfection of the camera, or more precisely its lens. Besides, it is necessary to set up the relation between the real dimensions of the parts and their dimensions expressed by pixels. The calibration process helps to compensate for the image distortion and to define the scale between the pixel size and real work piece size. In the next step the calibrated digital image needs to be processed through the edge detection algorithm and contour creation program.

3.1.2. Object identification and location

In this work the Sobel algorithm is used for the edge detection (Sonka, Hlavac and Boyle 1998). The edges represent continuous pixel chains which delimit the regions in the image. In the segmentation process (Yang and Gillies 2004; Haralick and Shapiro 1992), the "border tracking" algorithm is used to create the corresponding contours, interpolating the detected edges. The contours are formalized as splines.

The recognition algorithm generates hypotheses about the objects from the image, comparing the created contours with the contours created from the CAD model. The recognition is based on the classification algorithm. The result of the recognition gives the list of identified objects with corresponding information about their positions (x, y coordinates) and orientations (α rotation angle in xy plane). If one object is recognized more than once in the same image, all of its instances are included in the list.

3.1.3. Creating and formatting recognition model from CAD

The recognition model is a formalized structure which describes the geometry of the part that should be identified and located by the vision system. To create the recognition model from the CAD data it is necessary to generate a 2D drawing first. The drawing of a part should include corresponding views, i.e. orthogonal projections that are expected from the camera view. The drawing is an analytical representation of geometry and needs to be transformed into the format compatible (comparable) with the image from the camera, i.e. from the digitizer or frame grabber. Therefore, the drawing must be transformed into the matrix format.

The matrix representation is then treated in the same way like the image from the camera, including the segmentation, i.e. contour tracking, and calibration.

3.1.4. Preparing the results for the robot

The recognition is limited to the objects defined by the assembly plan. The result of recognition is sorted according to the given assembly sequence (Kunica and Vranješ 1999). Originally, the homogeneous transformations define the position and orientation of the parts relative to the vision system world. In order to be applicable to the control program of the robot, the transformations should be changed into the robot’s coordinate system by multiplication with the homogeneous transformation describing the relative position of the vision system and the robot coordinate system. Finally, the sorted and transformed recognition results define grasping coordinates.

3.1.5. User interface of the vision system program support

The user interface of the vision system program is designed to help the definition of important parameters and the visualization of the recognition process.

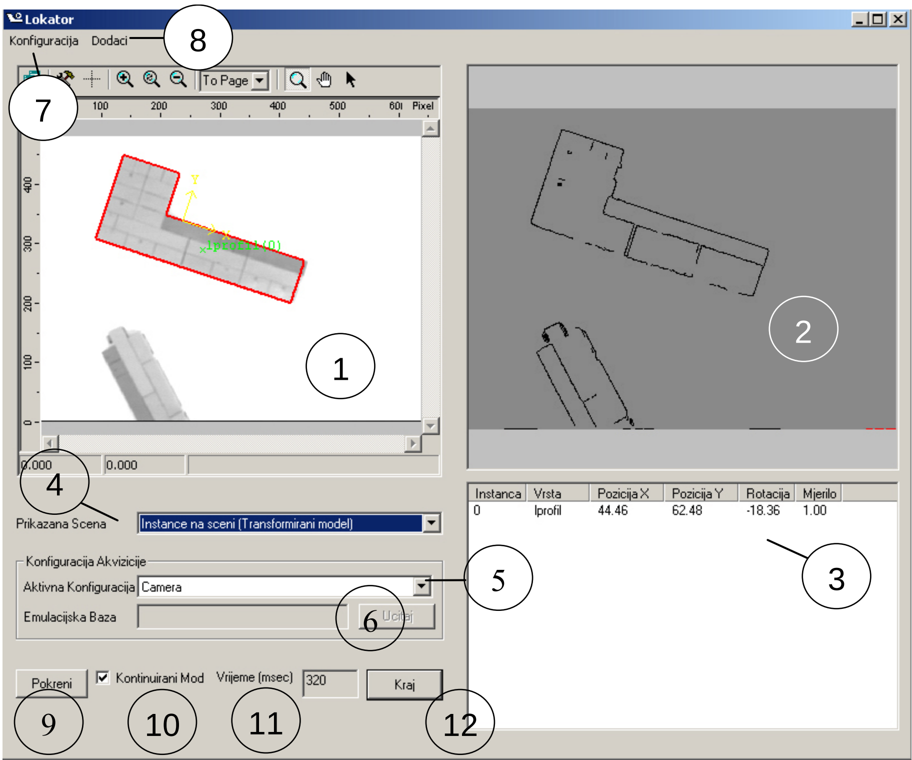

Figure 3 Interface of the vision system

Slika 3. Sučelje vizijskog sustava

Figure 3 shows the screen capture of the graphical interface of the vision system program. The numbers indicate the following elements:

1. input image window
2. detected edges
3. table of discovered instances,
4. window selection menu
5. input image menu
6. emulation base selection
7. configuration menu
8. adds-on menu
9. inspection start button
10. continuous mode
11. time elapsed by inspection
12. end button.

3.2. Recognition model extraction from CAD data

The process of the recognition model extraction is based on the following:

- Creating of digital images from the corresponding drawing views of the parts
- Generating of the emulation base with monochromatic images
- Calibration of the images.

The complete process of extraction is given in Figure 4. The process starts with the 3D CAD model design. Then 2D projections are generated by standard drafting tools. The drawings are initially described in the 2D vectorized format.

The images for emulation base should be defined in the 256-bit MS Windows bmp (bitmap) format, compatible with the monochromatic image from the frame grabber. Since the CAD software is usually not able to generate bitmap image, the drawing is saved in the standard vectorized Adobe PDF format.

The pdf format can be transformed into the matrix format by using some commercial image processing software like Adobe Photoshop. The matrix resolution should be defined before image loading. The drawing loaded into the image processing software can be cleaned from unnecessary drawing elements or details in this phase. The saved bitmap image should be now calibrated in the same way as an image from the camera.

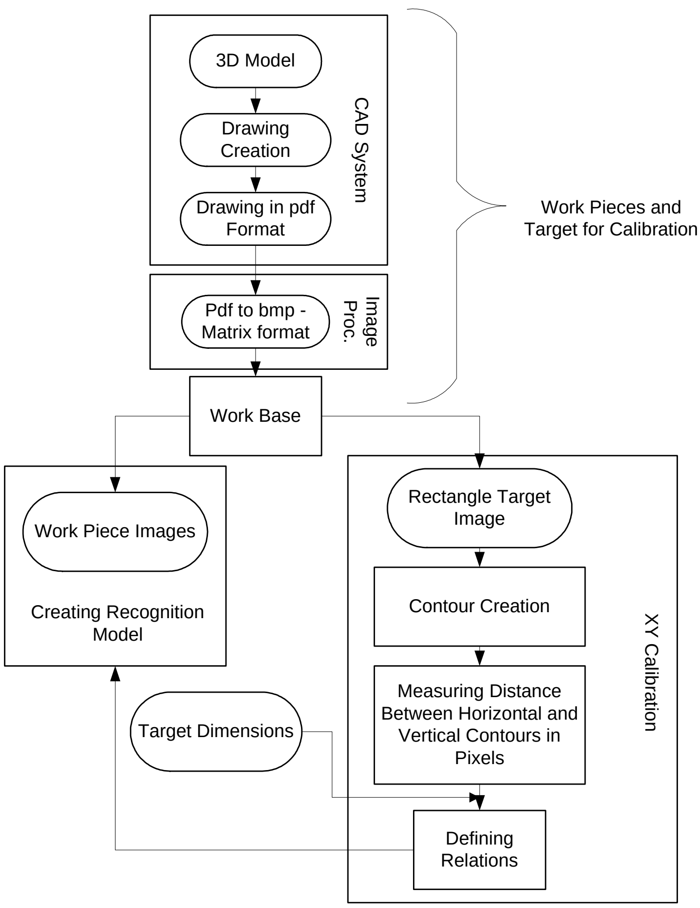

Figure 4 Procedure for the creation of the recognition model from CAD model

Slika 4. Postupak stvaranja modela za prepoznavanje iz CAD modela

3.3. Robot control program

The robot is managed by the control program which is running on its own control unit. The program is actually parametric pick & place routine. There are two parameter sets which define an assembly task. The first set includes grasping positions and orientations, obtained from the vision system. The second set defines the trajectory parameters for the case when some of the assembly actions require a specific approach given by the assembly plan.

The control program is developed in V+ programming language (Adept 2001). The program structure is given in Figure 5.

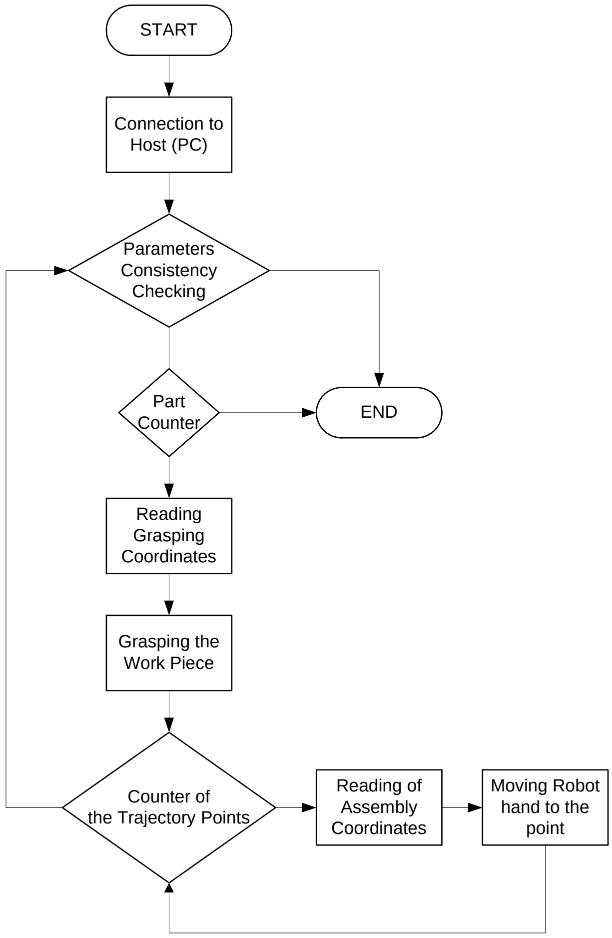

Figure 5 Structure of the robot's control program

Slika 5. Struktura upravljačkog programa robota

Since the robot gets the required parameters from the PC, the control program must establish the TCP/IP connection first. The parameters are stored in three files on the PC:

– The first file contains positions and orientations of the parts
– The second includes the information about the approach heights
– The third file comprises trajectory parameters.

The control program uses the NFS protocol to download the files from the PC. It verifies the data consistency, comparing the names and the number of the parts with the assembly plan data.

The pick & place algorithm is divided into three segments: approaching the part from above, moving to the grasping position and departing.

The grasping transformation is defined by three Euclid coordinates and three Euler angles. The angles ν and φ are constant and have the value of 0^o and 180^o respectively. The vertical Z coordinate is defined from the working plane height, expressed in the robot's base coordinate system increased by the relative grasping height. The other parameters: X, Y coordinates *and* ψ angle, are given in the first file which is generated by the vision system.

3.4. Assembly process

After the part has been picked up, the operation of part mating starts. This operation is defined by the assembly trajectory from the corresponding assembly plan. The trajectory is described by the position and orientation vectors r. The trajectory file contains the array of interpolating vectors. The operation ends when the last location has been reached. The control program continues with the next part until all parts have been assembled.

4. Application and verification of the developed system

The application and verification of the automatic assembly system developed to work in a disordered environment is demonstrated on a simple product presented in Figure 6.

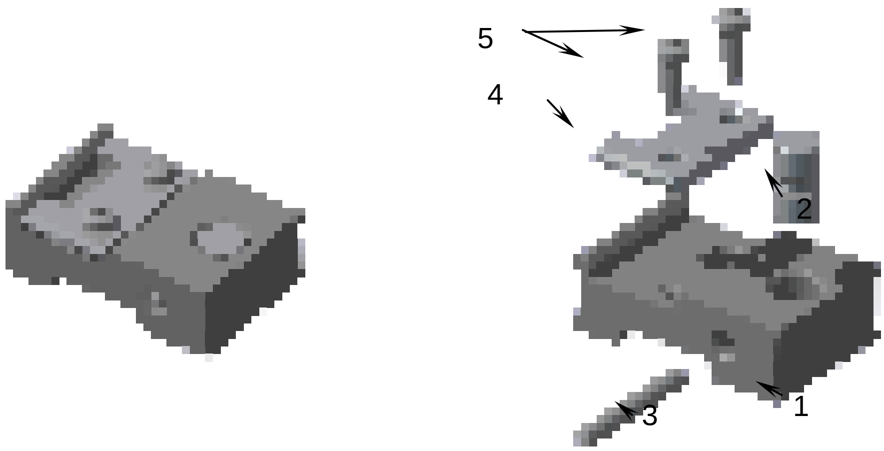

Figure 6 The experimental assembly
Slika 6. Eksperimentalna montaža

The product is designed as a hypothetical artifact for research purpose. It consists from 5 parts (numbered according to the corresponding assembly sequence), which involve some of the most important and frequent assembly operations:

1. base part, 2. cylinder, 3. pin, 4. plate, 5. screws.

4.1. Model verification

The system, run by the integrated program support developed in this work, is presented in Figure 7. There are three work planes within the robot working area. The one in which the robot expects the parts in random state is covered by the vision system. The robot is supposed to pick up the parts from that plane and move them to the place where assembling is expected to be carried out. After the assembly process has been finished, the robot should move the product onto the unloading place.

Figure 8 shows some of the assembly operations and parallel recognition results.

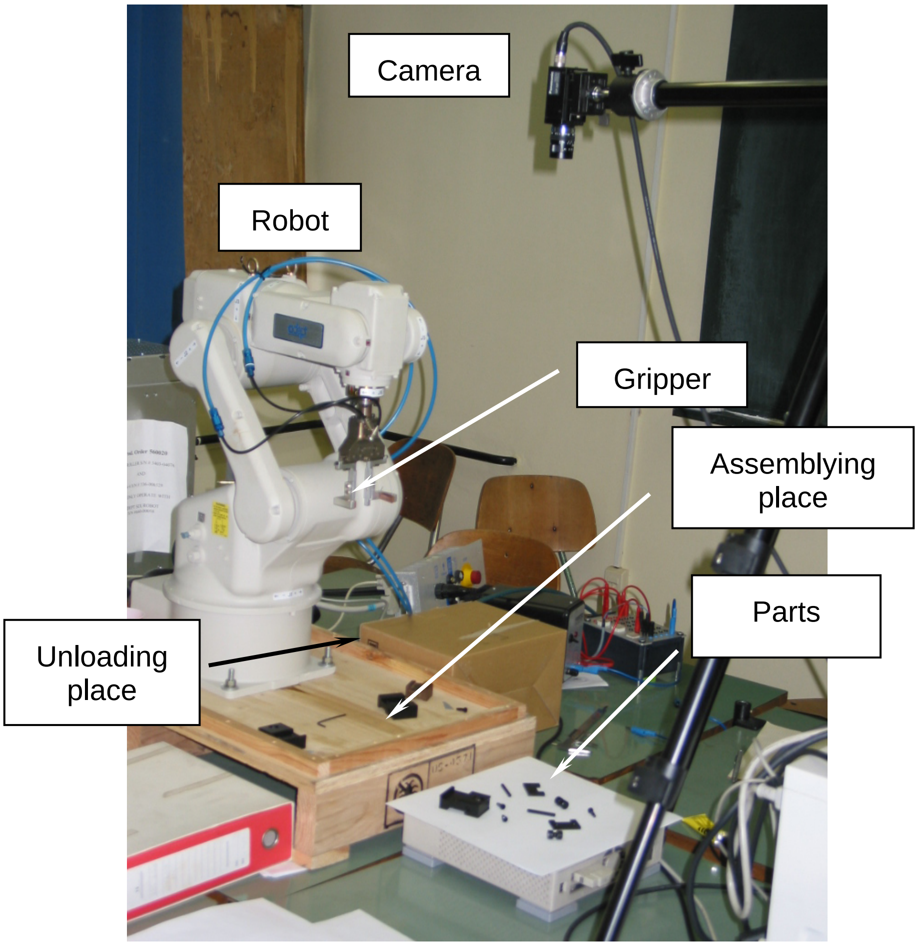

Figure 7 Intelligent robotic cell

Slika 7. Inteligentna robotska jedinica

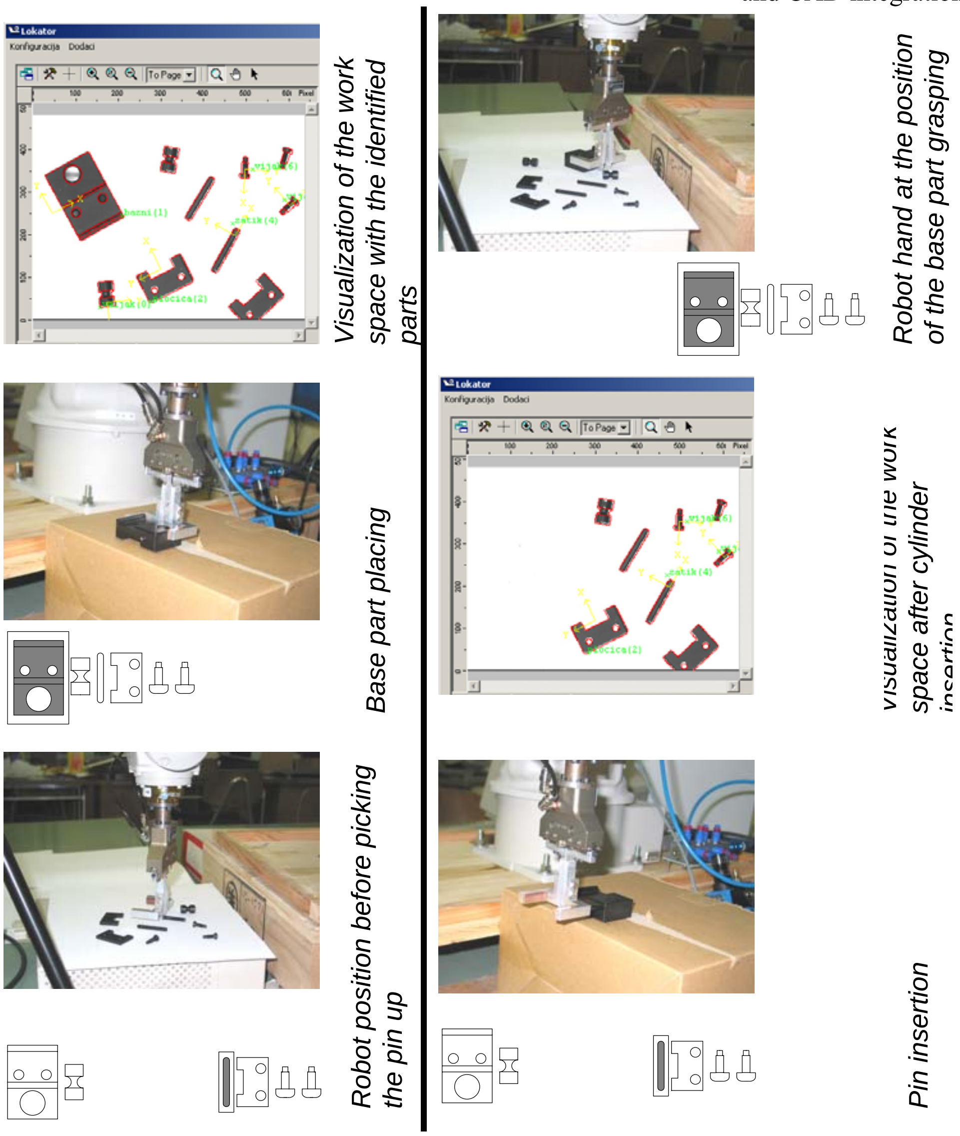

Figure 8 Presentation of assembly experiment

Slika 8 Prikaz eksperimenta montaže

5. Conclusions

In robotic/automatic assembly, the information about the position and orientation of work pieces and all other in-process relevant objects represents the essential data for control programs. Location data directly influence handling operations, which are usually the most difficult automation tasks. Automatic handling operations generally presume a deterministic environment, where all spatial configurations are precisely anticipated. However, deterministic chaos inevitably obstructs absolute expectations, always producing slightly changed situations. Despite that, the conventional automation methods tend to create technical systems as almost perfect constructions. It seems that such efforts are definitely hopeless and result in expensive and inefficient systems. The deterministic chaos should be accepted as a natural phenomenon and the development philosophy should change toward the development of intelligent machines capable of adapting their behavior according to the natural imperfect world where nothing is absolutely ideal or accurate.

The model of autonomous intelligent assembly system presented in this work reflects the attitude stated above. The complementary driving idea was the information integration, actually, the connection between engineering knowledge generated through the product design cycle and process knowledge required to drive/control machines. A corresponding autonomous robotic system has been built to verify the proposed model.

Machine vision is one of fundamental elements in the developed system. The related program support provides the recognition and location of freely distributed parts within the robot's work space. Thanks to the machine vision, some undefined and physically disordered system conditions become deterministic and information consistent.

The recognition process uses two sources of information: a camera and a CAD model. The image from the camera represents the current/real situation in the robot's work space. The CAD models, actually their drawings, constitute the knowledge base, or virtual models, for recognition. The machine vision program establishes the recognition process based on the comparison between these two sources of information/knowledge. The vision program developed in this work includes the following subroutines/tools:

- Recognition and location
- Data management
- Recognition model generation
- Visualization of results.

The basic vision functions are realized by the commercial Adept HEXSIGHT vision tools software.

The robot control program integrates the machine vision results and assembly process plan. In this way all essential data are provided for the realization of autonomous assembly operations.

An experimental autonomous robotic cell has been realized according to the proposed model. The practical verification proves the robustness of the integration of engineering CAD knowledge (virtual product) and process algorithms. Therefore, the vision system does not need the training based on the real part scanning and bitmap tuning. Generally, the CAD models of a product and a system, designed in the computer virtual world, represent the source of all information needed during the process of product materialization. Such approach is a contribution to the integrated engineering, product and production development (IEPPD).

Further research directions point toward two domains. The first implies the development of 3D robotic vision based on a moving camera attached to the robot end joint. The object recognition based on 3D models could provide more flexibility in the environment perception and in solving more complicated tasks.

The second research direction addresses the development of artificial intelligence methods, in the domains of control and machine vision, with the aim to raise the level of machine working autonomy.

Acknowledgements

This work is part of the research project "Machine Intelligence in Assembly", supported by the Ministry of Science and Technology of the Republic of Croatia.

REFERENCES

[1] Adept Technology Inc.: 2001, *HexSight User Guide*, Adept Technology Canada, Santa Foy.

[2] Adept Technology Inc.: 2001, *V+ Operating System User's Guide*, Adept Technology, San Jose.

[3] Adept Technology Inc.: 2001, *V^+ Language User's Guide, Version 14.0*, Adept Technology, San Jose.

[4] Buhmann JM, Malik J and Perona P: 1999, Image Recognition: Visual Grouping, Recognition and Learning, *Proc. of National Academy of Sciences*, 96(25), 14203-14204.

[5] Chakrabarty S and Wolter J: 1997, A Structure-Oriented Approach to Assembly Sequence Planning, *IEEE Transactions on robotics and automation*, **13**(1), 14-29.

[6] Haralick RM and Shapiro LG: 1992, *Computer and Robot Vision*, Adison-Wesley, Reading.

[7] Jain, R, Kasturi R and Schunk BG: 1995, *Machine Vision*, McGraw-Hill, Inc., New York.

[8] Jerbic B: 2002, Autonomous robotic assembly using collaborative behavior based agents, *International journal of smart engineering system design*, **4**(1), 11-20.

[9] Jerbić B, Grolinger K and Vranješ B: 1999, Autonomous Agent Based on Reinforcement Learning and Adaptive Shadowed Network, *Artificial Intelligence in Engineering*, **13**(2), 141-157.

[10] Jones RE, Wilson RH and Calton TL: 1998, On Constraints in Assembly Planning, IEEE Transactions on Robotics and Automation, 14(6), 849-863.

[11] Kunica Z and Vranješ B: 1999, Towards automatic generation of plans for automatic assembly, *International Journal of Production Research*, **37**(8), 1817-1836.

[12] Minsky, ML: 1963, Steps Toward Artificial Intelligence, *in* J Feldmann, EA Feigenbaum (eds), *Computers and Thought*, McGraw-Hill; New York, pp. 406-450.

[13] Adept Technology Inc.: 2001, *Adept MV Controler User's Guide*, Adept Technology, San Jose.

Predano: datum (date)
Submitted:

Prihvaćeno:
Accepted:

Bojan Jerbić
Božo Vranješ
Miljenko Hrman
Zoran Kunica
University of Zagreb
Faculty of Mechanical Engineering & Naval Architecture
Ivana Lučića 5, Zagreb, Croatia