A Systematic Approach to Automated Gear Assembly *

Uwe Heisel; Stefan Schwock; Frank Richter

Abstract
Automated assembly of gear wheels requires exact orientation of the tooth profiles in order to avoid collision and damage during the joining process. Various tactile and contactless methods can be applied for the orientation of gear wheels. A systematic overview of these methods is compiled in the presented paper. As a conclusion of research carried out at the Institute for Machine Tools, setups for contactless orientation detection using inexpensive senor devices show significant advantages. Application of these methods and sensor concepts contributes to the realization of economical operation of automated assembly systems.

Keywords: *Assembly, Automation, Gears*

Introduction

For the last decade, automation of production processes has been a major objective of factory rationalization. Despite vast automation, increasing costs in all areas of manufacturing indicate that economical solutions have to be implemented in order to take a pole position on a competitive market. In particular, automated assembly systems often operate unefficiently, due to expensive periphery and special sensing equipment [1]. In the following, strategies for automated assembly of gear wheels and the required sensors for orientation will be discussed. Additionally, a selection of low-cost sensors and sensing strategies has been examined and tested. Results of the sensor selection can also be used for other applications where orientations and positions have to be detected.

Gear Assembly and Orientation Detection

Automated assembly of gears in flexible assembly systems requires accurate orientation of the parts to be joined [2]. In order to implement the process of orienting and joining toothings economically, a fast and reliable method has to be developed. Besides speed and reliability, flexibility is required with respect to teeth characteristics and wheel dimension. Furthermore, small and medium batch sizes should be processed without manually changing the sensor configuration [3].
Basically, two strategies are possible for the assembly of gear wheels. These strategies are divided according to their main direction into radial and axial joining (fig. 1). The decision which strategie to apply largely depends on the teeth characteristics.

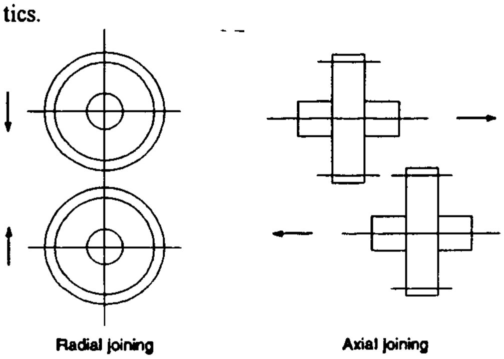

Fig. 1: Radial and axial joining of gear wheels

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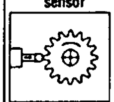
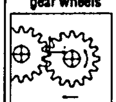
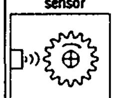
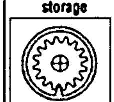
Double helical gearings, helical gearings and herringbone gearings can only be joined in radial direction, whereas spur gearings can be joined both ways, radially as well as axially.
Joining axially requires pre-orientation of the gear wheels in order to avoid damage to gear wheels and handling devices. Joining radially may require pre-orientation depending on the type of gear to be assembled. If there is a possibility for damage of the tooth surfaces, e.g. if the gear wheels cannot rotate freely or in the case of worm gears, the gear wheels have to be pre-oriented, too.
Basically, several concepts exist to engage gear wheels in an automated assembly process (tab. 1). In order to determine the orientation of gearings, two different sensing methods can be applied: tactile and contactless sensing. Tactile sensing can be subdivided into two further strategies. On the one hand, the orientation can be detected using a tactile sensor, such as a touch probe. In this case, the probe touches the surface of the toothing

detection of orientation	*location of orientation detection*	*evaluation*
tactile	sensor 	- application of low-cost sensors possible - all wheel materials - different location of detection and assembly - touch probes have to be changed for different tooth modules
	gear wheels 	- detection of orientation during assembly - all wheel materials - high sensor costs - time consuming due to signal processing
contactless	sensor 	- application of low-cost sensors possible - no damage during orientation detection - all wheel materials
none	storage 	- simple setup - no sensors required - not very flexible regarding wheel size - difficult application for worm gears, helical and herringbone gears
	gear wheels 	- works for all wheel materials - no sensors required - not applicable for all teeth characteristics - compliance of one wheel required

Tab. 1: Overview of strategies for automated gear assembly

in order to determine the position of the tooth space and the tip of the tooth. On the other hand, the orientation can be determined during the actual joining process of the gear wheels by using one of the wheels as a touch probe. With this method, a force sensor is required and the force signal has to be monitored to detect contact of the tooth surfaces. According to the measured force signal, the wheel to be joined is iteratively reoriented until a final position is reached.

Contactless sensing of the wheel orientation can be applied if contact forces between the tooth surfaces have to be avoided during assembly. Here, orientation of the wheels is performed before the actual assembly process is carried out. The main advantage using contactless sensors is that damages of the tooth surfaces caused by collisions of the teeth are omitted.

Furthermore, the gear wheels can be placed in a storage already oriented. This method requires no sensors during assembly. However, not all teeth characteristics allow oriented storage and special storage devices are required for each wheel dimension.

Finally, gear wheels can be joined without determining orientations at all. In this case, one of the gear wheels must be allowed to rotate and to deflect towards the opposite direction of the resultant force in case of collision of the wheels. Therefore, suitable grippers with compliance elements have to be developed. However, this method can only be used for gears with parallel axes. For gears with crossed or intersecting axes, such as worm gears or miter gears, this assembly strategy cannot be applied, due to restrictions caused by the method of bearing, gear box design and lack of space for deflection movements.

The orientation of the tooth position can be determined in radial direction or in axial direction (fig. 2). Both methods are suitable for all teeth characteristics except for worm gears, where only the radial method can be applied. Pre-assembled bearings with diameter greater or equal the diameter of the gear wheel also can disturb axial detection, e.g. in the case of a matrix scan sensor with axial detection direction.

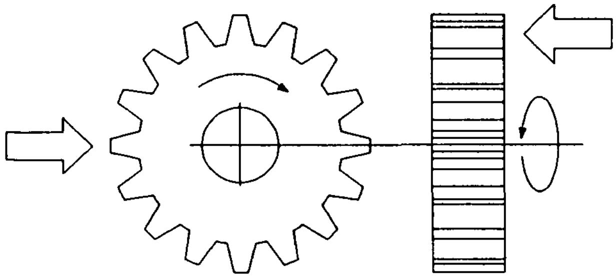


Fig. 2: Radial and axial detection of tooth position and wheel orientation

Selection of Applicable Sensors

Generally, methods based on the physical effects of induction, capacity, magnetism, and the reflection of light, air, and sound are suitable for contactless detection of objects. In table 2 common contactless sensors are summarized and typical operative ranges are listed. Most important for the applicability is the minimum required scan area, since it is related to the minimum tooth module that can be sensed with a certain type of sensor. This criterion therefore restricts the use of capacitive and ultrasonic sensors. The electric field of the capacitive sensor, respectively the sound field of the ultrasonic transducer, is too large and therefore the resolution is not accurate enough [4]. Furthermore, switching distance as well as switching interval (respectively measuring distance and measuring interval for measuring sensors) are of importance for the practical use of the sensors. For automated handling of gear wheels with robots, for example, the switching distance should not be less than the repeatability of the robot used in the setup in order to avoid collisions and damage of the sensor device. At the same time, the switching interval should be large enough to allow inaccurate positioning of the toothing by the robot.

Tab. 2: Overview of common contactless sensors and their ranges of operation

sensor type	direction of sensing	min. scan area (diam.)	switching distance Sn	switching interval	limiting frequency	workpiece materials	price	installation work	remarks
unit		mm	mm	mm	Hz				
inductive sensor	rad./ax.	1,5	0,6..2,0	0..Sn	250..1000	conductors	low	low	only small diameter sensors
capacitive sensor	rad./ax.	-	-	-	-	conductors	-	-	not applicable, very low resolution
ultra sonic sensor	rad./ax.	-	-	-	-	all materials	-	-	not applicable, very low resolution
impact pressure sensor	rad./ax.	2,5	0,3	Sn+0,5%	< 10	all materials	low	low	slow response
optical reflex sensor	rad./ax.	1	50..100	Sn +1%	150..800	all materials	medium	medium	
light barrier	axial	0,2	0..200	0..200	10.000	all materials	medium	low	
laser light barrier	axial	0,05	0..50000	> 1000	5.000	all materials	medium	low	
laser position sensor	axial	1	60..140	60..140	700..3000	all materials	high	medium	
line scan sensor	axial	var.	100.. 1000	var.	var.	all materials	high	very high	
area scan sensor	axial	var.	100.. 1000	var.	var.	all materials	very high	very high	

All listed sensors, except the impact pressure sensor, have sufficiently high limiting frequencies and therefore short process cycles can be achieved. The process time for line scan sensors and area scan sensors usually depends on the processing speed of the secondary processing equipment such as personal computers. Due to complex calculations [5] the limiting frequencies for these image processing systems can be as low as 1 Hz. For the processing of gear wheels made of different materials, optical sensors are advantageous, since they can be used for any material if surface characteristics allow sufficient reflection. Problems can arise if there is diffuse reflection or disturbing external lighting, e.g. by changing solar radiation.

At last, price and required installation work are important economical criteria which should be taken into account when selecting a sensor system. Switching sensors with their low costs and simple installation are more economical than measuring systems that require special processing equipment such as computers and additional programming.

Operation of low-cost Contactless Sensors

Due to economical aspects and simple integration, contactless sensing low-cost sensors are suitable for application in automated assembly systems. Following, operation ranges and characteristics of an inductive proximity sensor, an impact pressure sensor with PE-transformer and an optical reflex sensor are examined closely.

Minimum cycle time is an important criterion for application of sensor concepts. The cycle time of an orientation process is determined by the rotational velocity of the gear wheel, which has to be rotated within the range of operation of the specific sensor. In figure 3 maximum circumferential speeds depending on tooth module for the three sensors are shown. Additionally, the obtained values are a measure of the reaction time or sensitivity of the sensor.

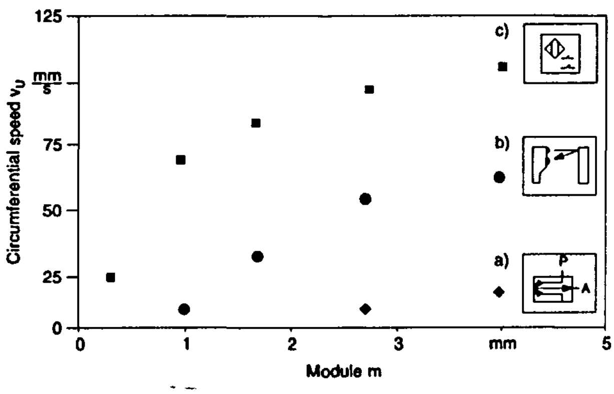


Fig. 3: Maximum circumferential speed for gear wheels with different modules and different contactless sensors (a. impact pressure sensor with PE-transformer; b. optical reflex sensor; c. inductive proximity sensor)

Closely related to the maximum circumferential speed is the limiting frequency and the resolution of the sensor, respectively of the data acquisition system, e.g. the robot controller. Figure 4 displays the relationship between circumferential speed and resolution of the sensor system for different limiting frequencies. From this relationship in the form of $a_u = v_u / f$, where v_u is the circumferential speed and f is the limiting frequency of the sensor-data-acquisition system, a_u yields the maximum resolution on the perimeter of a gear wheel. For example, with a circumferential speed of 50 mm/s (robot rotating gear wheel) and using an inductive proximity sensor with a sampling frequency of 1000 Hz, a resolution of 0,025 mm on the perimeter of the gear wheel can be achieved.

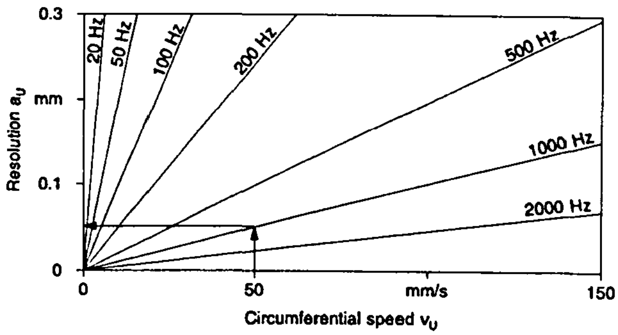


Fig. 4: Possible resolution on the perimeter of a gear wheel depending on the circumferential speed and the sampling frequency of the sensor system

Sensor Signal

Since all examined sensors are switching devices, rotation of a gear wheel in front of a sensor supplies a periodic binary signal as sensor output. Figure 5 shows a signal typically measured during sensor operation. As a reference, the actual tooth position was recorded with a contactless position transducer.

Two strategies can be used in order to determine the actual tooth position during normal assembly using the shown signal. First, the rising side of a sensor impulse can be used as a reference for orientation. Since the edge separating tooth flank and tip of a tooth cannot be detected accurately, a random position on the tooth flank is taken as a reference mark of the wheel orientation. Experiments have shown that the rising slope of the binary signal is triggered reproducibly at the same position on the tooth flank. In this case, no further processing of the signal is required. However, knowledge of the position of the random reference mark on the tooth flank with respect to the tip of the tooth has to be determined in practical tests.

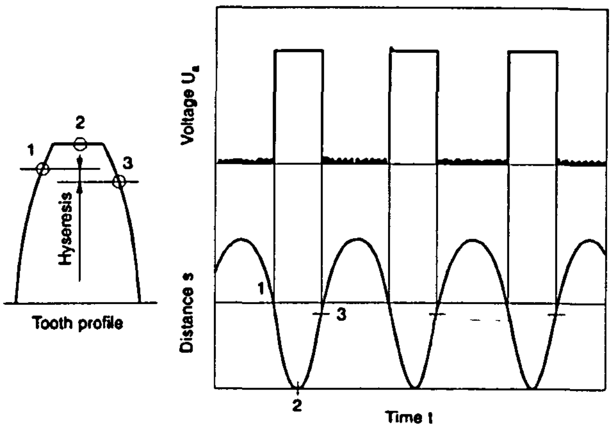


Fig. 5: Correlation between sensor output signal and real tooth position signal

As a second strategy, the width of a sensor impulse can be used to calculate the position of the tip of a tooth. If the gear wheel is rotated for half a sensor impulse width after detection of the rising slope, the middle of a tooth is positioned directly in front of the sensor. Consequently, no preceding test have to be carried out to find an offset to a reference point on the flank surface. This is an advantage if wheels with different diameters are assembled, since it reduces programming time for the robot. However,

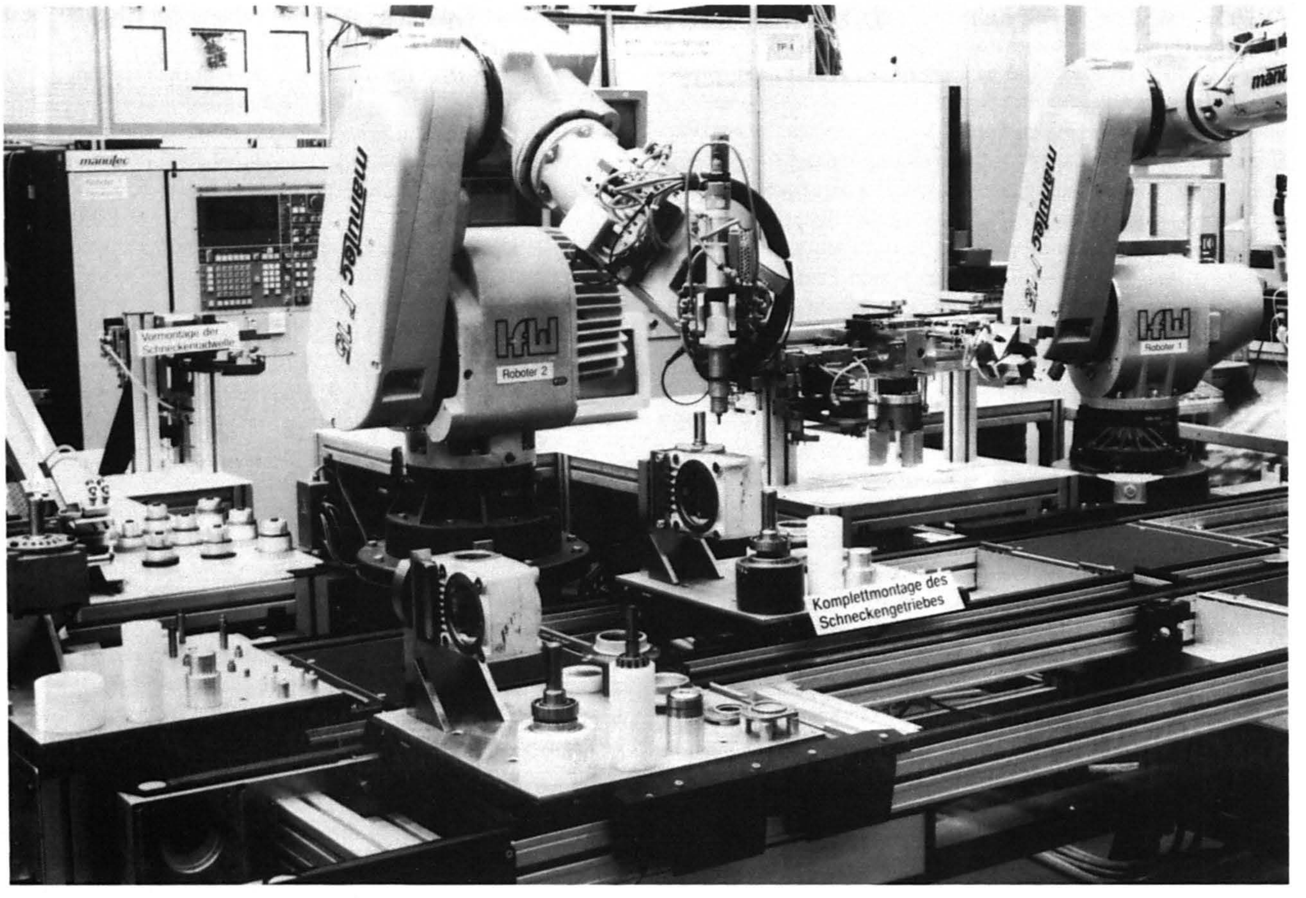


Fig. 6: Flexible, automated assembly system for worm gears at the Institute for Machine Tools, University of Stuttgart

during tests small deviations at the position of the falling slope of the sensor impulse due to hysteresis effects (fig. 5) have been observed. Therefore, small inaccuracies result when determining the exact wheel orientation.

As a recommendation, the method described first provides a very reliable and reproducible way to determine the position of an tooth on a gear wheel, whereas the second method should be used, if gear wheels with different diameters and modules have to be assembled in a single assembly cell.

Example: Automated Assembly of Worm Gears

In an assembly system for worm gears at the Institute for Machine Tools (fig. 6) two strategies for the orientation and assembly of gears were tested. First the tactile sensing of the orientation in the gear box with a six axes force torque sensor was implemented [1, 2]. Iteratively, the gear wheel was moved into the final position by processing values and directions of the forces resulting from the collision of the tooth surfaces. The complete joining process was finished within about 30 seconds.

Second, for the contactless sensing of the orientation, the signal of an inductive proximity sensor is connected directly to the digital input of the robot control. Diameter, module and offset of the reference point (if required) for the wheel to be assembled are transferred from the supervising computer, e.g. the cell controller, to the robot control. The robot picks up a gear wheel and rotates the wheel in front of the contactless sensor. The position of the teeth on the perimeter of the gear wheel is determined according to one of the methods described above and the proper orientation is calculated and set by the robot control. Finally, the wheel is moved to the gear box and assembled. With this pre-orientation of the gear wheels time savings of approximately 50% compared to tactile sensing are possible.

Conclusions

Research and carried out experiments have shown that the use of low-cost contactless working sensors leads to economical solutions for the orientation of gear wheels in automated assembly. The proposed setup with the determined parameters of operation supply accurate and reproducible results which allow joining of gear wheels without damage.

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