“MORITZ” a Pipe Crawler for Tube Junctions

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Abstract

This paper deals with the further development of the tube crawling robot “MORITZ”, which was built at the Technical University of Munich. This robot can climb through pipes of different inclinations. It is improved in the recent research project, so that it also can manage tube junctions. After a brief introduction about problems concerning such a robot the used gait pattern is explained. Additionally some simulation results - showing the load at the robot during a motion through a tube crossing - are presented. Moreover the new developed joints in the central body as well as the sensors are described. The paper ends with a brief description of the crawler's control and its modifications for the new climbing maneuver in tube crossings.

1 Introduction

Leakages of pipe systems lead to a loss of the transported medium and may have a harmful effect on the environment. Therefore companies like the chemical, the power supply or the waste water industry require machines for the inspection and repair of their large pipe systems. Currently such robots are driven by wheels, chains or they float with the medium. Another possibility to realize the movement is to use a legged locomotion, which allows a higher flexibility than the common systems. Rossman [5, 6] built such a crawler (figure 1 left) at the Technical University of Munich. It is able to crawl in tubes of any inclination from horizontal up to vertical pipes. The robot also manages curved pipes with a diameter of $60 - 70\,cm$. To enable this the crawler is equipped with eight legs each with two driven joints, which can achieve torques up to $78\,Nm$. To move the crawler spreads four of its legs against the pipe wall to generate friction forces. These can carry its weight of $20\,kg$ and an additional load, while the other four legs swing to the next stance point. During this motion the robot control has to ensure permanently that there is sufficient friction force to bear the robot. However “MORITZ's” movement is limited to its working room limitations.

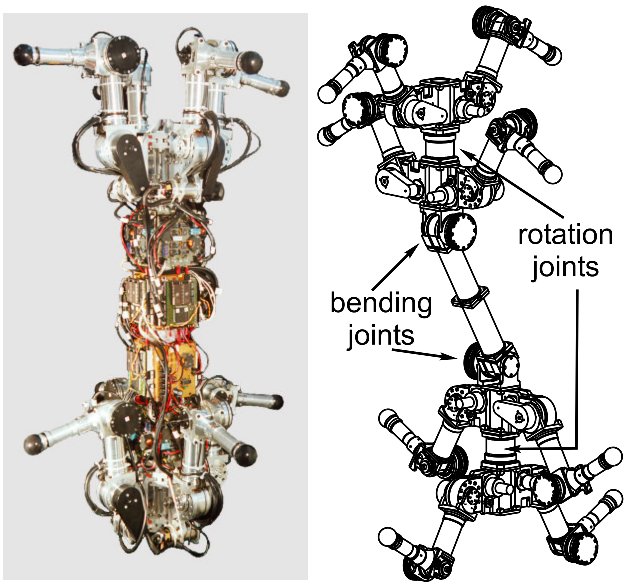

Figure 1: Pipe crawling robot “MORITZ”

The current research project aims to enhance the crawling capabilities of this robot to enable it to climb through pipe junctions. To make this possible the control has to find suitable stance points for the implementation of the movement. The analysis of the gait pattern, the joint angle limitation and the length of the leg showed that new joints (two bending joints and two rotation joints) have to be implemented in the central body (figure 1 right). The two bending joints divide the central body into three parts - the front and rear body, on which the legs are mounted, and the middle body. This configuration allows the robot to bend its central body and to maneuver in crossings, which are located in this bending plane. The other two joints (the rotation joints) separate each group of legs into two leg pairs to allow a rotational motion around the longitudinal axis of the crawler.

In section 2 the gait pattern will be described in more detail. Section 3 shows simulation results and in section 4 the design of the joints are explained. The used sensors as well as its redundancies is explained in section 5. Finally the control of the robot is described in section 6.

2 The gait pattern

To climb through the pipe the robot has to spread its legs against the tube wall to generate the necessary friction forces. Therefore two leg pairs, each consisting of two opposite legs, are needed to bear the robot (stance phase) while the other legs swing to the next stance point (air phase). Because of the limited degrees of freedom in each leg (only 2 degrees of freedom) those four legs are used to bear the robot, which lie in one leg plane (e.g. legs 1, 3, 5 and 7 in drawing plane of figure 2). When the legs, in the air phase, reach

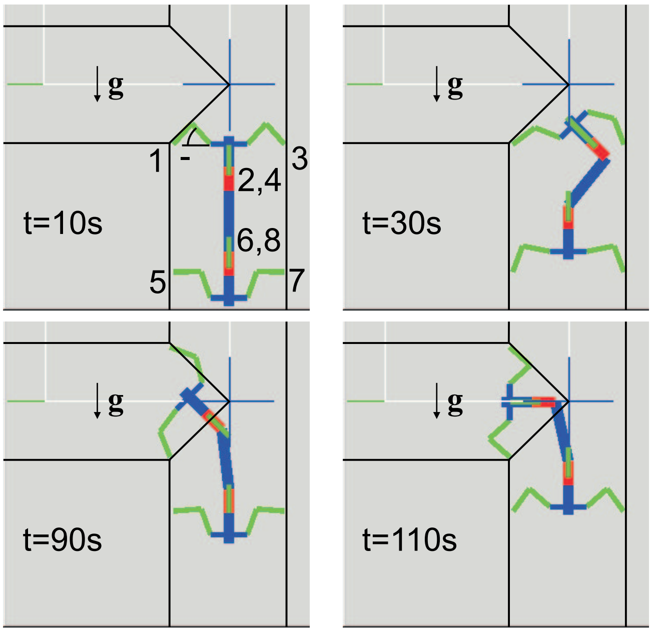

Figure 2: The gait pattern

their new stance points, their tasks are changing and they will have to bear the robot, while the other ones can change into the air phase and swing ahead. Due to this alternating bearing planes a three dimensional motion of the central body is realized.

To achieve a movement through a tube junction the following modifications are necessary. First of all the robot has to rotate around its longitudinal axis to get its bending plane parallel to the junction plane - both planes are parallel to the drawing plane in figure 2. Therefore the robot spreads in the pipe either with its outer or inner two leg pairs. Then the robot rotates the two leg pairs on the front and the rear body that are in the air phase to the new position. For this movement the robot requires the rotation joints. After that the robot changes its bearing plane and orientates its leg planes into normal position (figure 2, $t = 10\,s$). Now the bending joints allow to bend the central body as shown in figure 2 ($t = 30\,s$). At this position the bearing plane is alternated again (legs 2, 4, 6 and 8 are bearing the robot) and therefore the front and rear body can achieve a motion only in their bearing planes. That is the reason why the middle body is needed. The middle body decouples the forward motion of the front body from the rear body and thus avoids a drilling friction in the stance feet. In the following the bearing plane alternates again and the robot will be in position $t = 90\,s$. The robot finally bends its front body completely into the intersecting tube ($t = 110\,s$). Analogical to this the rear body will move into the intersecting tube.

3 Simulation results

To analyze the motion under different joint configurations and to determine the loads at the joints as well as the structure a multi-body simulation program was developed. The examination of these joint con-

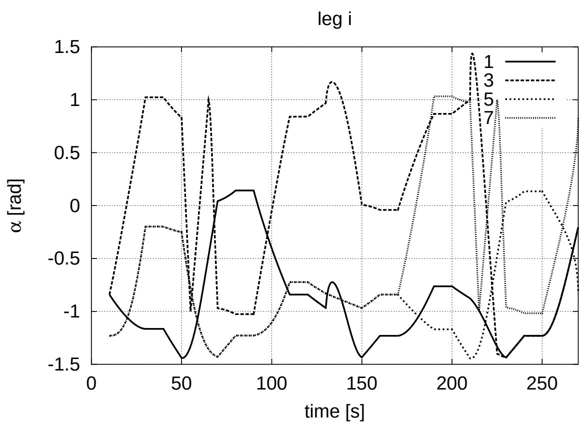

Figure 3: Leg joint angle α

figurations resulted in the concept with four new joints as described above. To simulate the motion of the robot a target path is given, which was transformed into minimal coordinates via a newton approximation. Figure 3 shows the angle α for the legs in the bending plane during the maneuver through a tube junction.

α describes the angle between the central body and the first leg segment, while $\alpha = \pm\frac{\pi}{2}$ means that the leg segment is parallel to the central body. The joint angle never exceeds the limitation of $\pm\frac{\pi}{2}$.

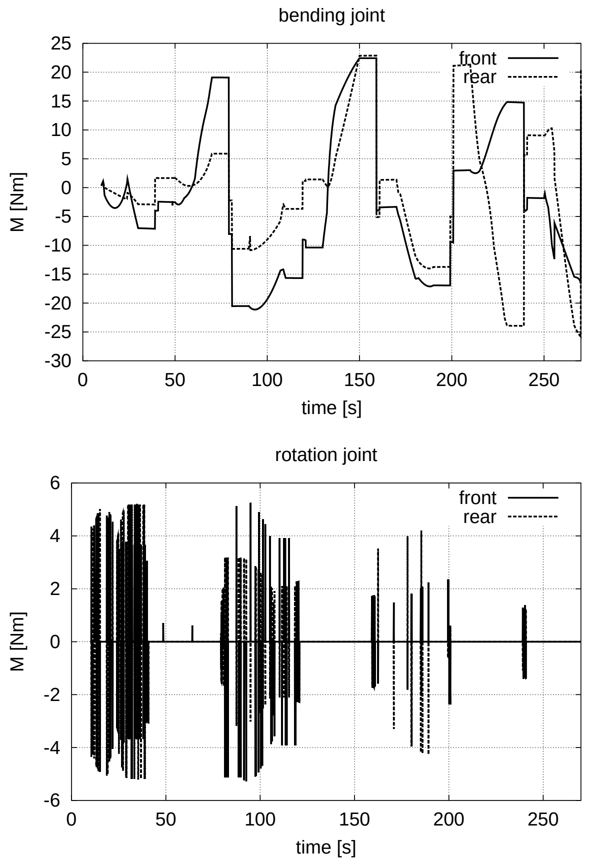

Figure 4: Torques of the central body joints

For the load determination an optimization of the feet forces is necessary. This optimization is realized with a linear programming under the quality function

$$\max_{\forall \text{ joints } i} \left(\frac{|M_i|}{M_{i,limit}} \right) \longrightarrow \text{MIN!}$$

and the following constraints:

- The target position has to be observed.
- The friction constraint must be fulfilled, which means that for the linear programming the friction cone has to be linearized to a friction pyramid.
- The limits of the drives $M_{i,limit}$ have to be observed.
- A maximal foot force of 350N must not be exceeded. This limitation is necessary due to a implemented force sensor.

The quality function was chosen to minimize the maximal joint load. For the solution of this min-max-problem, it can be transformed in a linear programming if all constraints are linear [3]. In figure 4 the computed joint moments of the central body are shown. The loads at the rotation joints result from the large lever arm (matching the pipe diameter) and small differences in the friction forces lateral to the leg plane.

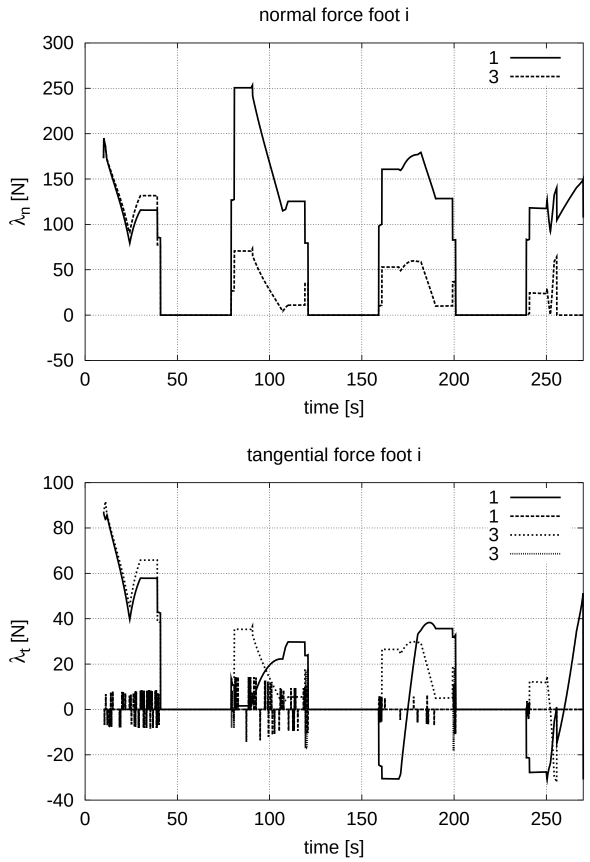

Figure 5: Forces of the front feet

Figure 5 shows the normal and tangential forces at the two front legs, which are lying in the bending plane. Comparing the results with the positions visualized in figure 2 it can be shown that the normal force in leg 3 decreases. This results from the direction of the gravitation vector **g** which causes leg 1 to bear the robot while the normal force in leg 3 generates an additional load. The remaining normal force in leg 3 is used to generate a friction force for the compensation of the tangential force. The tangential forces between $t = 10\,s$ and $t = 4\,0s$ are used to bear the robot in the vertical pipe and thus have to be generated out of the normal force. The tangential force of leg one for the time period $t > 50\,s$ is smaller than the generated friction force.

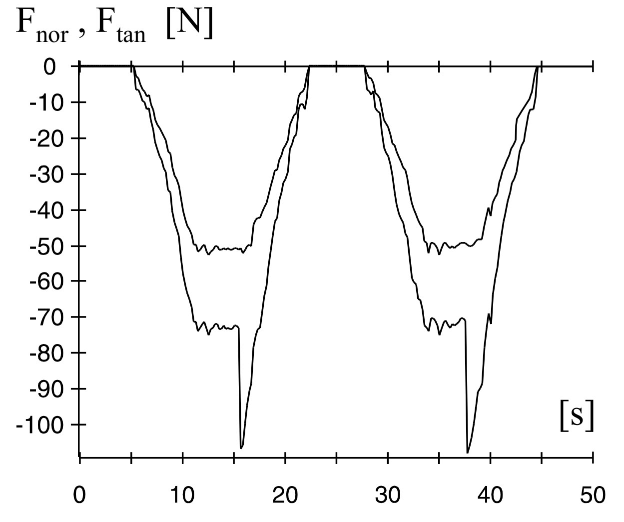

Figure 6: Measured leg forces for a motion in a vertical tube with friction coefficient $\mu = 0.75$

A further verification is done by comparing the simulated forces for the redesigned robot with the measured ones of the present robot (Figure 6). In order to get comparable results we consider a motion through a vertical pipe combined with a force optimization analog to the one described above. Due to the existing limitations in the gait pattern only the first time period can be compared. It can be seen that the tangential force is 30% greater than the measured force, which corresponds to the increased weight of the robot. The difference between the normal forces results from the reduced friction coefficient of $\mu = 0.5$ for the simulation. Based on this and further simulations of the climbing maneuver in different conditions the gait pattern as described is selected. Finally the simulated loads of the central body joints serve as estimation for the joint construction.

4 The central body joints

The great amount of joint as well as the demand for a low system weight, which is required for this kind of motion, claims for a light weight and space-saving design. Due to the existing power supply, DC motors in combination with Harmonic-Drive-gears have to be used. With respect to the simulation results ESCAP motors 35NT2R82, which have a good efficiency weight and a compact size, are selected. These motors admit a continuous torque of 0.115 Nm. That is the reason why gears with a reduction of $i \approx 480$ are needed for the bending joints. This gear reduction is generated by a bevel gear with $i = 3$ and a Harmonic-Drive-gear (HD-gear) HFUC 20 with $i = 161$. Figure 7 shows the design of the bending joint.

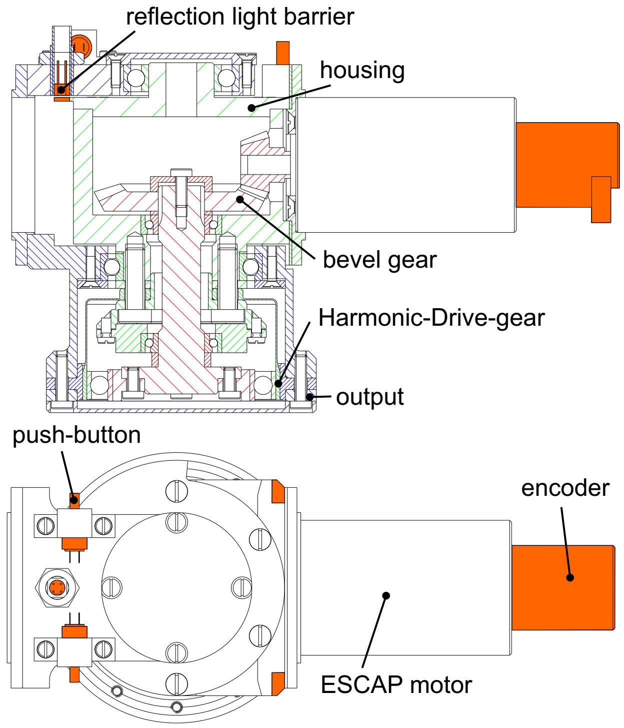

Figure 7: The bending joint

The motor actuates the drive shaft, which is fixed to the wave-generator of the HD-gear via the bevel gear. The drive shaft itself is bedded by two angular contact bearings in the housing, to which the middle body of the robot is connected. The flex spline is fixed to the housing and thus the output is connected to the circular spline of the HD-gear. This output is bedded in the housing with two ball bearings, because only small axial forces have to be transmitted from the legs to the central body.

For the design of the rotation joint the same motor is used, but due to the smaller loads and the different rotation axis another gear ratio as well as another mounting is selected. A HD-gear HFUC 17 with a reduction of $i = 121$ is sufficient and allows a high transmission accuracy as well as a high angular repeatability. This time the motor drives the shaft and thus the wave-generator of the HD-gear directly. The drive shaft is again bedded in the housing with two angular contact bearings, to which one of the inner leg pair is connected. The flex-spline is also fixed to the housing thus connecting the output again to the circular-spline. But this time the output is bedded via two angular contact bearings, due to the great bending torques, which have to be transmitted from the output to the housing. Figure 8 shows the design of the rotation joint.

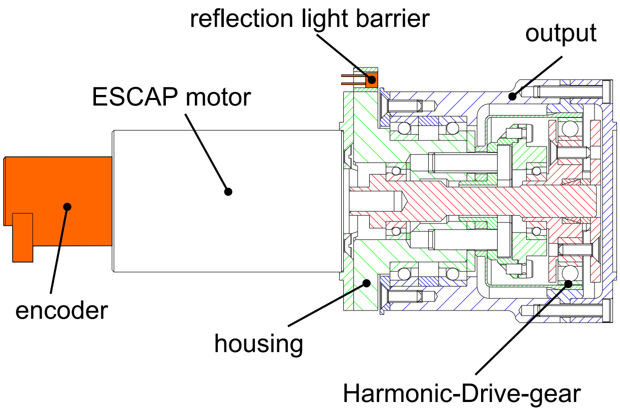

Figure 8: The rotation joint

5 The sensors of the crawler

Each leg has two actuated joints and thus two potentiometers for measuring the angles and two tachometer generators for measuring the angular velocity. This redundancy is used by the robot control to evaluate both sensor signals for integrity and therefore can halt the robot to avoid damage if one sensor fails.

Also a light weight force/torque sensor, which was developed for this robot [5], is integrated in the outer leg segment. Gálvez improved this sensor not only to measure the contact forces but also to allow the controller to determine the normal vector in the contact point of the foot [2, 7].

For the control of the central body joints sensors are needed to measure the angle and angular velocity. Both is done via encoders which are connected to the motors. However this kind of sensor would lack the sensor's redundancy as well as the possibility to determine the correct reference point. The reference signal which is sent by the encoder is repeated every revolution of the motor and thus wouldn't be unique. To solve this problem a reflection light barrier is implemented in the joints which divides the adjusting range into two parts, one with reflection and another one without. On the one hand this signal is used to find the correct rotation direction on startup, to get the transition point from the reflected area to the unreflected one. On the other hand this resulting transition point signals that the next encoder reference defines the authentic reference. Finally, to solve the redundancy problem two different solutions are realized. For the bending joint two push-buttons are mounted which shut off the power of the motors when the joint reaches the end of the adjusting range. The redundancy of the other joint is done with a second reflection light barrier which signals faulty angular positions to the controller which will shut off the power of the motors. Therefore the sensors are mounted in a way that ensures that only functional light sensors send a faultless signal. Both senor systems can be seen in figures 7 and 8.

The advantage of the encoder over the analog sensors is a higher accuracy of the determination of the angle as well as a reduction of computation time and measurement noise. In an experimental setup a resolution of 2000 signals per motor revolution is reached for all new joints. But due to the restricted computation power of the microcontroller rounding errors must be expected in the control computations.

6 Crawler control

For the control of the robot all sensor signals are evaluated by five Siemens C167CS microcontrollers, which are mounted on the central body. One controller acts as a central unit, while each of the remaining four units controls a leg pair. A CAN bus system is used for the communication between the microcontrollers. Thus it is possible to give simple control commands or to get information about the system via an external PC.

The implementation of a decentral control architecture similar to the one of the six legged walking machine [1, 4] enables to divide the whole control problem into different subproblems. On the one hand the controllers have to ensure that the legs are coordinated with each other and on the other hand they have to execute the operations. Each of the two task levels (the coordination level and the operating level) can be divided again into a central and a local part. Figure 9 shows this task distribution.

- The *central coordination level* coordinates the characteristic phases of the two leg planes. The controller decides which legs have to bear the load and which ones can swing ahead to the next stance point on their own. Furthermore, problems which can only be mastered by a reaction of the whole robot are solved on this level (e.g. the legs of one plane cannot find a contact point in their whole working area). Therefore this control level also can influence the local coordination level.

- The *local coordination level* controls the changes between the different leg phases (stance, protract,

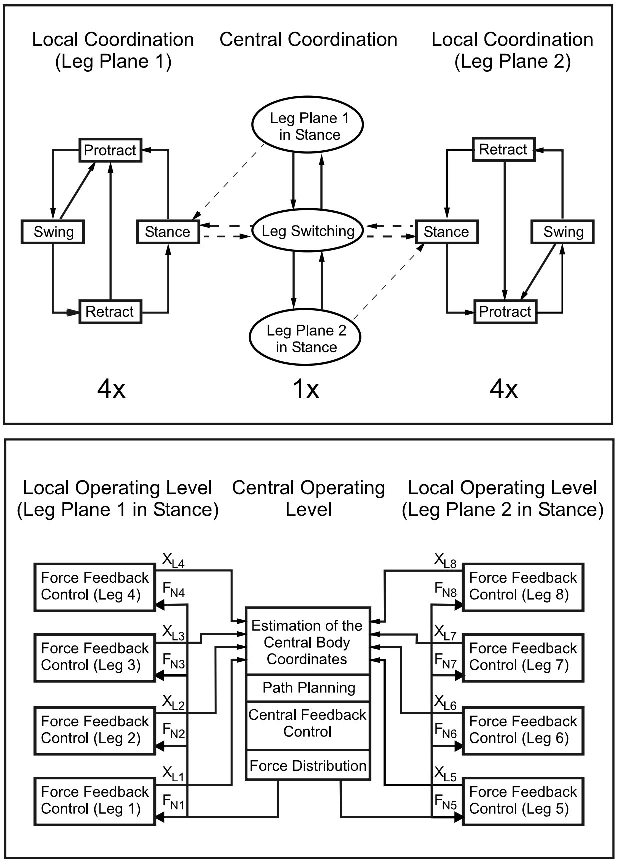

Figure 9: Control scheme for the crawler

swing and retract). If a predefined event occurs the controller switches to the corresponding leg phase. For example a leg in swing phase is switched by the local coordination level to the retract phase, if the leg has passed a geometric limit in the front area. The central coordination may influence this process under certain conditions. This control level also reacts to disturbances like avoiding small obstacles or finding no contact.

- The *central operating level* controls the positions and the velocities of the central bodies. For this purpose an appropriate force distribution is computed to determine the joint torques similar to the one described in section 3. These joint torques are then sent to the local operating levels.

- The *local operating level* controls the applied forces during the contact phase and the motion during the different air phases of a single leg. While the motion in the air phase is really a local control problem, the leg forces in the stance phase are strongly coupled and therefore the force control cannot be implemented without a corresponding communication between the leg controllers.

7 Conclusion

In this paper the tube crawling robot “MORITZ” as well as its improvements to climb through tube junctions are presented. “MORITZ” is able to move with a legged locomotion through pipes of any inclination and bears its weight only with friction forces. For the new features the robot gets four new joints in the central body which allows to rotate in the pipe and to bend its body. The gait pattern that will be used to walk through a pipe crossing is explained and a simulation describes this movement. The optimization, which is used to distribute the feet forces, is elucidated. Afterwards the design and the sensors for the new joints are explained. Finally the control concept, which is divided in decentralized versus centralized tasks and in coordination versus operating tasks, is described.

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