

## ДОДАТОК А

Публікація за темою досліджень





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## MANIPULATORS WITH ELASTIC JOINTS AND THEIR CONTROL SYSTEMS

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Currently, the development of manipulators with variable mechanical elasticity has not reached the stage of industrial application, but is mainly concentrated in the world's leading robotics laboratories. Meanwhile, manipulators with constant elasticity are being introduced in the collaborative robot market.

The DLR manipulator [1], shown in Fig. 1, according to the authors' ideas, should have all the properties of a human arm by using variable stiffness in all joints. The robot uses FSJ (Floating Spring Joints) joints, a proprietary design of DLR.



Fig. 1. DLR Manipulator

Robotic manipulators with multiple VSA joints, like David, require advanced control algorithms that can cope with elastic joints and the properties of a multiple input multiple output (MIMO) system.

A distinguishing feature of variable stiffness actuators is that the stiffness change mechanism adds an additional degree of freedom (DOF) to the joint and hence increases the system complexity. This also leads to an increase in control complexity. Regarding joint control, the literature mainly considers independent

control of position and stiffness by adjusting the position or torque of two joint motors [2].

For this manipulator, the developers propose a damping MIMO controller based on the decoupling approach [3]. The MIMO controller is a state variable feedback based controller for a linearized system along a nominal trajectory. Here the torque feedback is used to shape the dynamics of the system. This turns the MIMO system into a set of isolated single-input, single-output (SISO) systems, allowing the controller coefficients to be assigned to each joint separately. The consequence is a significant reduction in computational capacity and analytical complexity.

The control algorithm, consisting of four main parts, is presented in Fig. 2.

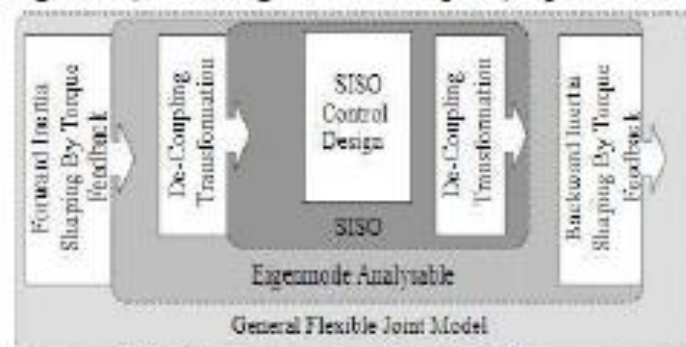


Fig. 2. Damping control algorithm [1]

In the first step, torque feedback is applied to form the motor moment of inertia as a diagonal matrix, which eliminates interconnections and allows each joint to be individually controlled. The system is then transformed to a new basis in which the system dynamics are written as independent fourth order differential equations. Next, the decoupled system is written as two second-order critical damping systems to achieve the desired damping behavior and determine the controller coefficients. In the final step, the controller is converted back to the original coordinate system.

The NASA Valkyrie humanoid robot [4], shown in Fig. 3, is based on SEA technology.



Fig. 3. NASA Valkyrie humanoid robot [4]

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The mechanical realization of the elasticity differs from one joint to another. The spring stiffness for each joint is chosen according to the desired amount of deformation at maximum torque.

The control system uses a decentralized approach as shown in Fig. 4.

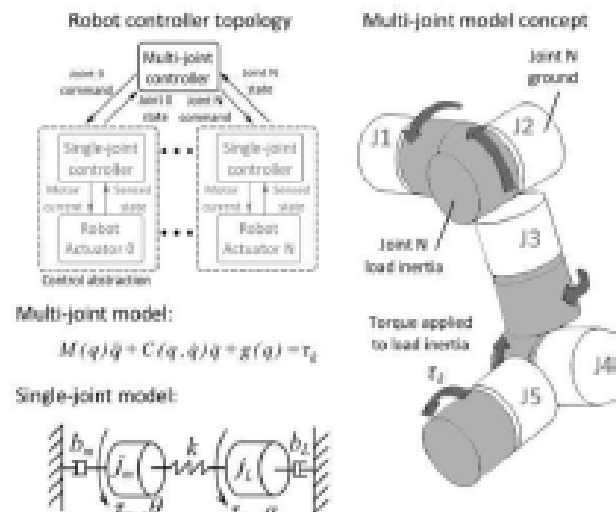


Fig. 4. Decentralized NASA Valkyrie control hike [4]

In the decentralized control approach used in NASA Valkyrie, the hinge level dynamics are decoupled from the central controller. The top controller views the robot as a collection of solids driven by joint torques. The output of this controller is the required torques, which are then sent to the lower-level controller of each joint (Figure 5).

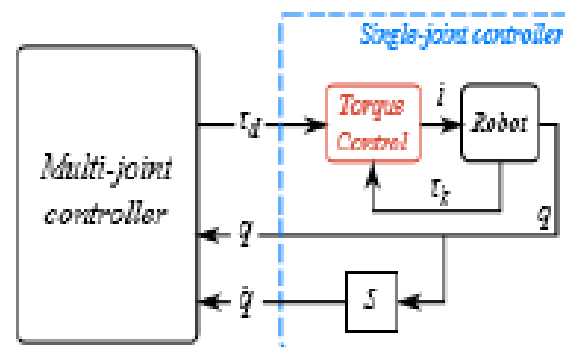


Fig.5. Torque control scheme [4]

Lower-level controllers model the dynamics of the actuator and provide the required torque. This approach differs from centralized control approaches that do not abstract the actuator dynamics from the overall robot model.

The ANYpulator [5], shown in Fig. 6, is built from lightweight carbon fibers and modular ANYdrive elastic joints developed at ETH Zurich. This enables dynamic motion, low-impedance torque control in the joint and safety of the interaction.



Fig. 6. ANYpulator with ANYdrive joints [5]

Here, a direct model-based force control method based solely on torque control in the joint is implemented. Using unified force and motion control, the position of the end link can be accurately and dynamically tracked in the task space while reacting safely to unexpected environmental contacts.

The torque control structure was adapted from the elastic joints used in the NASA Valkyrie robot [4]. The motor is considered as a torque source controlled by a lower level controller. The torque control loop of the joint is realized as a

PID controller with direct coupling compensation depending on the motor electrical constant and gear ratio. For small torque amplitudes in the joint, the proposed actuator system achieves a bandwidth of up to 70 Hz, which decreases at high amplitudes due to motor saturation effects.

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## ДОДАТОК Б

## Лістинг програми головного модуля системи main.py

```

# main.py
import time
from daq import SimulatedProcess, DataAcquisition
from analytics import AnalyticsEngine
from control import ПІДController
from comms import EventBus
from config import SENSOR_POLL_INTERVAL

def main():
    # Ініціалізація модулів
    process = SimulatedProcess(initial_value=20.0)
    daq = DataAcquisition(process)
    analytics = AnalyticsEngine(window_size=10)
    controller = ПІДController(dt=SENSOR_POLL_INTERVAL)
    bus = EventBus()

    # Приклад підписника на події (для логування)
    def logger(topic: str, payload):
        if topic == "sensor":
            print(f"[SENSOR]                               t={payload.timestamp.time()}
value={payload.value:.2f}")
            elif topic == "analytics":
                print(f"[ANALYTICS]
value_filt={payload.filtered_value:.2f}
anomaly={payload.is_anomaly}")
            elif topic == "control":
                print(f"[CONTROL] setpoint={payload.setpoint:.1f} "
                    f"measured={payload.measured:.2f}
u={payload.control_signal:.2f}")
                print("-" * 60)

    bus.subscribe(logger)

    control_signal = 0.0

    print("Запуск імітації кіберфізичної системи керування...\n"
          "Натисніть Ctrl+C для зупинки.\n")

    try:
        while True:
            # 1. Збір даних із "об'єкта"
            sensor_data = daq.read_sensor(control_signal)
            bus.publish("sensor", sensor_data)

            # 2. Аналітика
            analytics_result = analytics.process(sensor_data)
            bus.publish("analytics", analytics_result)

```

```
# 4. Керування (ПІД)
cmd = controller.compute(
    measurement=analytics_result.filtered_value,
    timestamp=sensor_data.timestamp
)
control_signal = cmd.control_signal
bus.publish("control", cmd)

# 4. Затримка (імітація реального часу)
time.sleep(SENSOR_POLL_INTERVAL)

except KeyboardInterrupt:
    print("\nЗупинка системи користувачем.")

if __name__ == "__main__":
    main()
```

**ДОДАТОК В**  
Демонстраційний матеріал

