Proceedings of the 1992 IEEE
International Conference on Robotics and Automation
Nice, France - May 1992

CONTROL SYSTEM OF SELF-MOBILE SPACE MANIPULATOR

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Abstract

Self-Mobile Space Manipulator (SM^2) is a simple, 5-DOF, 1/3-scale, laboratory version of a robot designed to walk on the trusswork and other exterior surfaces of Space Station Freedom. It will be capable of routine tasks such as inspection, parts transportation and simple maintenance procedures. We have designed and built the robot and gravity compensation system to permit simulated zero-gravity experiments. We have developed the control system for the SM^2 including control hardware architecture and operating system, control station with various interfaces, hierarchical control structure, multi-phase control strategy for step motion, and various low-level controller. The system provides operator friendly, real-time monitoring, robust control for 3-D locomotion movements of the flexible robot.

1 Introduction

Astronaut extra-vehicular activity (EVA) at a space station is costly, potentially dangerous, and requires extensive preparation. Some EVA tasks, such as unplanned repairs, may require the versatility, skill, and on-site judgment of astronauts. Many other tasks, particularly routine inspection, maintenance and light assembly, can be done more safely and cost effectively by robots.

Robots currently being designed for EVA work on Space Station Freedom are capable, but expensive and highly complex. NASA's Flight Telerobotic Servicer (FTS) and Canada's Special Purpose Dextrous Manipulator (SPDM) are examples of such EVA robots. These two human-size robots depend on other devices, such as the giant space station remote manipulator system and its spider-like mobile transport system, to transport them to space station work sites. This dependency could limit their usefulness.

We are developing a relatively simple, modular, low mass, low cost robot for space station EVA that is large enough to be independently mobile on the station exterior, yet versatile enough to accomplish many vital tasks. Because our design is for a robot that is independently mobile, yet capable of conventional manipulation tasks, we call it the Self-Mobile Space Manipulator or SM^2.

SM^2 walks on the nodes of a suitably scaled truss structure, and demonstrates capabilities of material transporting and simple manipulation. Optimized for the micro gravity conditions of space and sized to step between nodes that are 1.67 meters apart, the robot's links are constructed from thin-walled tubing to keep its mass to a minimum. This produces a robot that is highly flexible in structure, and controlling a 3-D locomotion movements of such a robot is a challenge. To simulate zero-gravity environment for realistic testing of the prototype robot's performance, we have developed a position servoed gravity compensation system utilizing video tracking and an innovative counterbalancing mechanism.

Salient features of the SM^2 control system include the hierarchical control structure, the multi-phase control strategy, and various robust low-level controllers. To execute the robot motion in different levels, from stepping sequences to joint motion control, the hierarchical control system is designed and can be executed autonomously or by various human interfaces in the control station. For the motion in a single step from one node to another, multi-phase control strategy has been implemented so that, for a large coarse motion we use a low-gain linear control or model-based control scheme with acceleration feedback to provide a stable, fast motion, while in a vicinity of the destination we use a high-gain control incorporated with an automatic vision system measuring the location of destination with respect to the robot tip.

We have developed dynamic model which has been verified by experiments and is being used for model-based control. The configuration-independent control scheme using simple gain scheduling, allows the control parameters to adapt to the dynamics changes due to the robot configuration variation. The adaptive control to the unknown object that is being manipulated or transported has been successfully implemented. With these robust controls, the robot system performance is highly improved subjected to the unmodeled dynamics due to unknown payload, modeling error, and disturbances. For the limited scope of the paper, we will not be able to address these advanced low level control algorithm, and interested readers may refer to our papers [2, 3, 1].

0-8186-2720-4/92 $3.00 ©1992 IEEE

2 Gravity Compensation System

The zero-gravity environment at an orbiting space station has significant impact on the design and performance of a robot. The absence of gravitational forces permits a long, spindly robot to move relatively large masses with small forces and power consumption. In order to perform realistic experiments on earth, we have developed two gravity compensation systems that balance the significant gravitational effects on the robot so it behaves as if weightless.

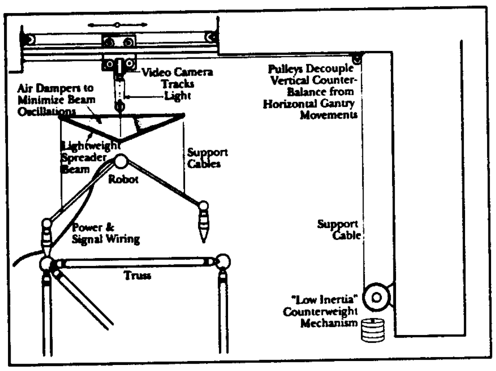

Figure 1 Gravity compensation system simulates zero-gravity for realistic laboratory experiments. A passive system of counterweights, cables and pulleys provides a constant, vertical balance force. A powered, overhead carriage is servocontrolled to keep the support point directly above the robot.

The first gravity compensation system (Figure 1) includes a passive, vertical counterweight system, and an actively controlled, horizontal system. The vertical system comprises a counterweight mechanism, a spreader beam, and a series of cables and pulleys. The counterweight mechanism provides a constant vertical force to the end of the support cable to balance the weight of the robot. Because of the 10:1 ratio of the mechanism, the counterweight moves very slowly, stores little energy, and consequently increases the inertia of the system by only 10% in the vertical direction. The support cable is routed through idler pulleys on the overhead structure and spreader beam in a manner such that horizontal motions of the carriage have no effect on the vertical balance force, aside from those due to pulley friction and inertia. The spreader beam transfers the force from a single support point to two balance points on the robot links. Its lightweight design and the use of kite-like air dampers minimize beam oscillations that can disturb the robot and gravity-compensation active control system.

The overhead carriage is actively controlled in the two horizontal axes to maintain the suspension point for the support cable directly above the robot so that the compensating force is purely vertical. A video camera mounted at the center of the carriage tracks an infrared LED at the center of the spreader beam. An automatic vision system locates the image of the LED in the camera's field of view, and generates error signals proportional to the horizontal displacement of the image relative to the camera. A motor/control system drives the carriage in two axes to minimize the error signal, thus keeping the carriage directly above the robot. Control gains are selected to give stable motion during large excursions of the robot; when the speed goes below a preselected threshold value, gains are automatically increased by the control system to minimize static error. The two-phase control strategy improves overall performance substantially.

The first gravity compensation system has allowed SM^2 to walk on one vertical face of the trusswork, and from one face to another with the truss at 45 degrees to horizontal. Discrepancies in the compensation forces due to friction and tracking errors amount to about 1% of the robot's weight in the vertical direction and 2-4% in the horizontal.

To improve dynamic response of the system, we have developed a second generation system. The configuration of the systems is in a polar coordinates, with tangential and radial motion actively controlled, and vertical motion compensated by a passive counterweight system. Two DOF optical sensors are mounted to measure the tangential and radial motions. The new system provides two, independent, actively controlled suspension points, needed for experiments in manipulation and payload transport, where additional weights must be supported. The new system has greatly improved the system performance and has been successfully used for experiments of fixed-base motion and manipulation.

3 Robot Design

SM^2 was conceived and designed to have the minimum size and complexity needed for walking on the space-station trusswork. The basic walker includes five rotational joints and two slender links (Figure 2). Grippers at each end of the robot enable it to attach itself to threaded holes in the truss nodes or other regular structure. Walking is accomplished by alternate grasping and releasing of the nodes by the grippers, and swinging of the feet from one node to the next. During each walking step, one end of the robot releases from a node, swings 90 or 180 degrees to a desired node location, and reattaches to that node. SM^2 moves along the trusswork using such steps with alternate feet. To minimize size, mass and structural compliance, the robot has sufficient span to just reach between adjacent nodes, a distance of 1.67 m on the 1/3 scale trusswork.

As a starting point in the robot development, we designed a hypothetical, full-size, self-contained robot to be used on the space station. The design included estimated masses of the major components: motors, drives, links, manipulation devices, and on-board power supply (batteries) needed for a reasonable travel range. The design also considered link and joint compliances, and the resultant structural vibration frequencies. Then a 1/3-size laboratory robot was designed and built using scaling rules to keep the dynamic parameters (masses, stiffnesses, natural frequencies, linear speeds) of the scaled-down robot similar to that of the hypothetical one. Overall dimensions of the truss and robot were reduced to 1/3, while local dimensions (truss nodes, joints and grippers) were kept equal (Figure 3). This allows the testbed to be used in an average size laboratory, while mechanisms are not unworkably small. Basic parameters for the full-size and scaled designs can be found in [2].

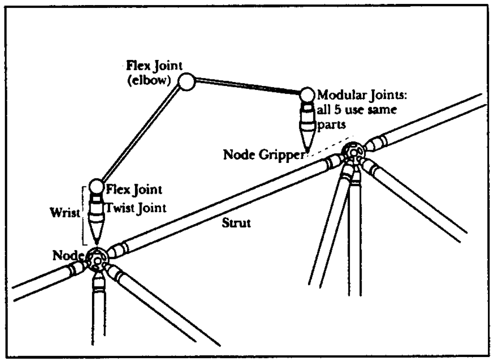

Figure 2 The robot has five joints connected by two slender links. Grippers at each end attach to threaded holes in the truss nodes, enabling the robot to walk by stepping from node to node.

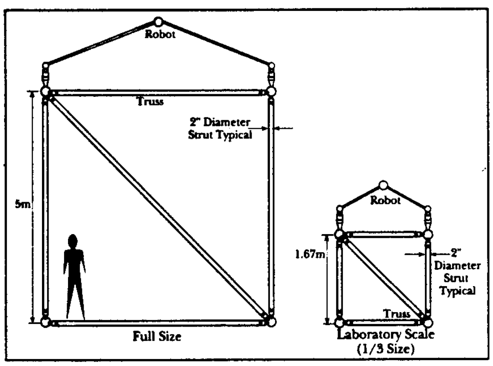

Figure 3 Overall dimensions of the truss and robot are scaled to 1/3 to permit experiments in the laboratory, while local dimensions (sizes of nodes, joints and grippers) are the same to keep local behavior similar, and mechanism size workable.

To simplify repairs to the robot and minimize the required inventory of parts, SM^2 was designed with five compact, modular, self-contained joints, all identical except for gear ratios. Each joint contains a rare-earth-magnet DC motor; harmonic-drive speed reducer (60:1 or 100:1 ratio) and joint angle sensors [2]. The motors and drive components were selected and arranged to give maximum power and torque in a small, lightweight package. A combination of conductive plastic potentiometer and incremental optical encoder provides both absolute position information and a low-noise signal for precise position and velocity measurement.

The node gripper, the device that attaches the robot to the nodes of the trusswork, is a critical part of the design. Unlike typical robot end-effector, it must be able to anchor the robot firmly to the nodes since the robot's base of support shifts from one end-effector to the other during walking. The node gripper [2] includes a motor-driven screw that engages the threaded holes in the nodes, and a cam mechanism that draws the gripper against the node with more than 1800 N (400 lb) of force. This large anchoring force is needed to prevent twisting or rocking on the node, which would disturb the robot's frame of reference. Signals from a gap-sensing button and motor-current sensor are used in the automatic control of the gripping and ungripping cycles.

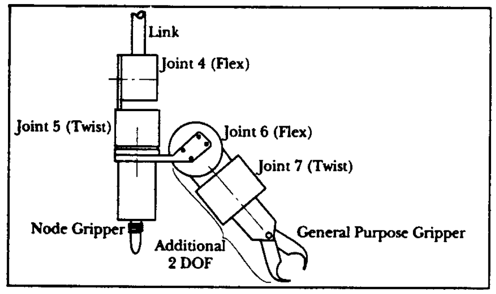

Figure 4 End-effector with two joints and general-purpose gripper will permit carrying and manipulation of parts.

We are developing an end-effector to enable SM^2 to carry and manipulate objects. This end-effector will have two joints of the same, modular design and a simple, general-purpose gripper, and will attach to the side of the node gripper [2]. The gripper will act as a controllable carrying device, and the combined 7 degrees-of-freedom (DOF) of the walker and end-effector will provide a general manipulation capability, (Figure 4).

4 Control Station

We are developing a control station designed for remotely controlling the robot system, taking advantage of both human guidance and the computer-driven controls of an autonomous robot. We want to provide smooth transitions from low-level, joint-specific teleoperation by an operator at the robot's control station through various levels of telerobotic control, where the human operator provides increasingly complex and higher level instruction to the robot, all the way to goal-specified, semi-autonomous operation. A hierarchical, video-display-based control structure allows the human operator to choose an appropriate level of control for a given task or robotic motion component. The control system is model-driven, so predictive displays are available for automatically controlled operating modes.

Using trackball, joystick, or computer mouse, the user interface presents the operator with an interactive visual display to specify the desired level of robot control. If the least automated mode of robot control, teleoperation, is selected from the menu display, then the operator may position the robot by using the computer display and one of the position control devices. The user selects which positioner he wants by rotating the box by the side of the controller's chair (Figure 5). Trackball or joystick would be used to control selected pairs of joints, while the articulated hand controller would be used to simultaneously specify all five joint positions. The Polhemus 6-DOF hand controller may be used to specify a target position for the robot's free end. This latter controller is an electromagnetic sensor built into a stylus grip that can detect its position, relative to a small transmitter module, within a radius of about 1 m of the transmitter. By analogy with the computer "mouse", we refer to the 6-DOF Polhemus stylus as a "bat" (i.e., a flying mouse). When the bat is selected, then computer mediation transforms the 6-DOF of the hand controller to the 5-DOF motion of the robot.

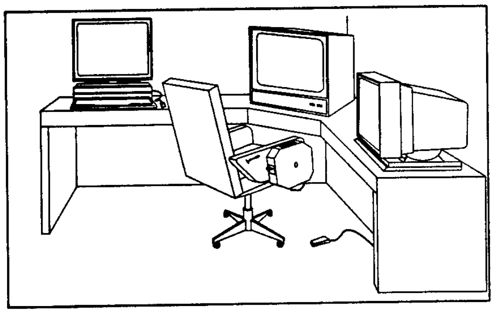

Figure 5 Control station. To the operator's left is a Sun workstation used to program the user interface. To the operator's right is the interface display for menu selections (see Figures 15 and 16). The monitor in front of the operator shows video from the camera mounted on the robot's active gripper. Hand controls (described in the text) are mounted to the chair's arm. The foot switch is to enable robot motion.

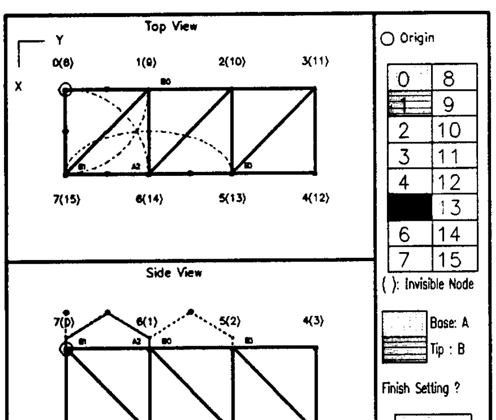

Figure 6 Screen graphics for control of multi-step paths. Operator selects target nodes along path to destination, then can preview simulated motion before commanding execution.

Different operation modes can be selected from the display menu [2]. Displays for higher level control allow the operator to specify a single step to a new position, or a sequence of steps starting with the release of a specified gripper and concluding with the insertion of the grippers at the designated target location (Figure 6). For these semi-autonomous walking modes, the operator may preview model-based animation of the robot's computer generated route prior to giving the locomotion command. He can then accept or modify the automatically planned route and monitor the robot's progress on the display. During actual locomotion, the robot animation is driven by the robot's joint position sensors.

During both direct teleoperation and the higher levels of telerobotic locomotion control, cameras mounted on the end-effectors provide the operator at the control station with visual feedback for final docking (insertion) maneuvers. Also used by the robot's machine vision guidance system, these camera views are most useful to a human operator during the insertion phase of the stepping sequence to ensure correct alignment.

5 Hierarchical Control Structure

Control software of SM^2 has been developed primarily for 3-D reliable and accurate locomotion movements on space station trusswork. Recently we have been working on tasks of material transporting and manipulation. In this section, we at first will discuss the hierarchical structure of the control systems that is executed in different levels. The system can automatically generate motion specifications, select the control parameters, execute the control, and monitor and display the execution. For a typical 3-D walking on trusswork, four-level control flow is shown in Figure 7.

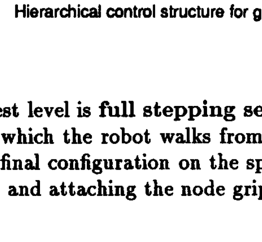

Figure 7 Hierarchical control structure for general walking

The highest level is full stepping sequences execution during which the robot walks from an initial configuration to a final configuration on the space station truss, by detaching and attaching the node grippers on the truss nodes. Considering each node on the truss as a sphere with threaded holes at 45 degree spacing, specifying the robot's two feet on two nodes of the truss, as an initial configuration and a final configuration, and then specifying the stepping motion traveling on each configuration, is too complicated. Instead, we developed a representation of the configurations and sweeping motion by using six parameters, so that optimal sequence of stepping motion on one face, or from one face to another, of the trusswork can be generated. The generated stepping sequences can be displayed on screen so that the operator can preview the stepping sequences to assure they are satisfactory before commanding automatic execution.

The next level is **single step motion control** during which only one of the node grippers moves from the initial node to the final node, to complete one step motion. The motion can be specified by the higher level, i.e., stepping sequences execution, or by an operator. In each step, the robot detaches from a threaded hole on a node, and sweep 90 degree or 180 degree about the first joint, and at the same time drives other joints to execute the specified trajectory, to the destination hole on the other node. For an efficient and accurate motion, we employed multi-phase control strategy in each step. Each step motion is decomposed into four phases: **extraction** from the attached node, **coarse motion** from the node to neighborhood of the destination node, **fine motion** to precisely locate the robot foot above the hole, and **insertion** on the destination hole.

Then, the following level is **single phase motion control** in which a single control law is implemented to optimize the performance in each phase. For the two levels that precede, low-level control structure and parameters are fixed, and only node-to-node motion can be generated. In this level, however, we can specify all possible low-level control structures, control parameters, trajectories, and initial and final locations within its workspace. Therefore, it is in this level we examine the controllers, trajectories, and performance. Various trajectories, such as parabolic and near-optimal trajectories [1], are available for a general motion. Since an arbitrary configuration can be specified and various controllers and trajectories can be executed, manipulation and payload transport experiments are also tesetd in this level.

The lowest level is **joint motion control**. The usage of this level is normally for testing joint controller, executing certain joint(s) without involving forward and inverse kinematics for special purposes, or checking sensor reading in each joint.

6 Multi-Phase Control Strategy

In this section, we discuss the multi-phase control strategy for the step motion addressed in the previous section. The control of SM^2, a 3-D flexible long-reach robot with possible large payload, is a challenge due to potential vibration caused by high flexibility, unmodeled significant joint friction, positioning error amplified by a long-reach, and unavailability of global tip sensing [1]. For such a system, it is difficult to achieve a reasonable speed, while at the same time retain an accurate motion. Moreover, for locomotion or other tasks in space applications, requirements for the robot performance vary for different periodic of time and different purposes. Based on this fact, we partition the step motion into four phases, **extraction, coarse motion, fine motion, and insertion**, (Figure 8).

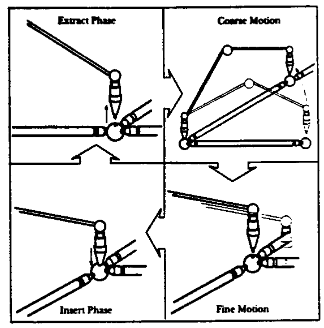

Figure 8 Automatic control of walking is divided into four phases, each tuned to optimize performance in that phase.

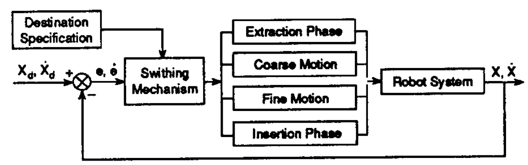

Figure 9 Multi-phase control strategy for step motion

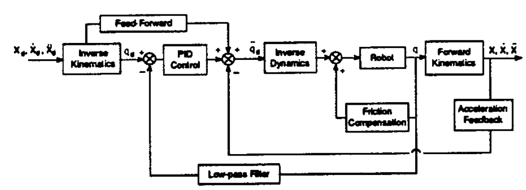

Figure 10 Block diagram of a typical low-level controller

In **extraction** and **insertion** phases, the robot motion is coordinated with control of the node gripper by using the gripper gap sensor and the motor current sensor. The goal in these two phases is to provide a reliable detaching and firm attaching, with a reasonable speed. In **coarse motion**, a fast and stable motion is desired, and the tracking error from the specified trajectory is not as important as motion efficiency. When the position error is within a certain region near the destination node, the motion phase is switched to **fine motion** in which the precise location is the main concern. The control block diagram is shown in Figure 9 where the *switching mechanism* is a function to determine the motion phase depending on the position and velocity errors with respect to destinations in each phase that are specified automatically for step motion.

In **coarse motion**, we implemented a linear joint controller with low integral gains and low-pass filters. The gains of the controllers, and the orders and the cut-off frequencies of the filters are determined by dynamic modal parameters obtained experimentally [3]. The sensor sampling rate is 50 HZ currently. The filter cut-off frequencies are normally set to 2-2.5 HZ to avoid the 3 HZ mode lateral vibration of the elbow joint. The closed-loop frequencies for the first three joints are set to about 1/6 of the filter frequencies, i.e., 1/3 - 1/2 HZ. Using acceleration feedback from the tip, a higher gain can be employed and filter delays can be compensated. A typical PID based low-level controller is shown in Figure 10. With this controller, the robot is able to execute a 90-degree sweeping step in 5 sec, a 180-degree step in 7 sec. A model-based control scheme is being developed for a fast coarse motion and the results have been promising [2].

In **fine motion, extraction** and **insertion** phases, a high gain control is implemented to minimize steady-state error, in order to achieve the precision needed for insertion of the node gripper. Because motion is relatively small and slow, and thus the deflection of structure will be also small in these phases, a linear structured control with high gains is feasible, and no model-based control scheme is needed. During fine motion, we use an automatic vision system at the end of the robot to measure the position error with respect to the destination node hole.

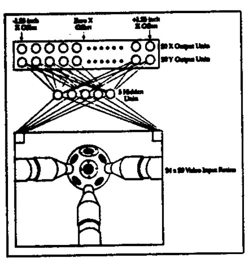

Figure 11 Low resolution video images from a camera mounted at the robot's tip are processed by a three-layer, back-propagation neural network. The output units give the x-y displacements of the tip from the target position.

The vision system uses a video camera mounted at the end of the robot to provide images of the target node. A 3-layer, back-propagation neural network processes the low resolution, 24x20-pixel video images (Figure 11). The output consists of two 20-element vectors representing the offset of the robot's tip relative to the node in the x and y dimensions. The network learns to analyze the image through a training procedure in which the tip is moved by hand around the vicinity of the node hole. Several hundred video images are collected while a special jig [2] measures the x-y position. Then a back-propagation algorithm is invoked to adjust the weights of the network's 2645 internal connections to produce the desired mappings between the input video images and output displacement vectors. After training, the vision system is able to recognize the target while processing images at 15 Hz, and provide error signals that enable the control system to bring the gripper screw into alignment with the hole. The neural network approach is particularly powerful because new or modified objects can be accommodated through a simple retraining operation.

The extraction and insertion controllers are identical, except no vision data are used in these phases. During extraction and insertion, additional signals from the gripper gap sensor and the motor current sensor are used to automatically control the gripper cycle.

Friction in the motors and harmonic drives is significant, compared to the joint torque generated. We have found empirically that the torque needed to overcome friction is more than 10% of the maximum joint torque, and nearly 50% of normal operating torques. To compensate for frictional effects, the control system increments the joint torque by a constant value in the direction of motion. This scheme improves static positioning accuracy at the tip from about 25 to 5 mm.

7 Summary

We have developed a simple, 5-DOF, 1/3-scale, laboratory version of a robot designed to walk on the trusswork of Space Station Freedom or other space structure. It will be capable of routine tasks such as inspection, parts transportation and simple maintenance procedures. We have designed and built the robot and gravity compensation system to permit simulated zero-gravity experiments. We have developed servocontrols for locomotion movements of the 3-D highly flexible robot and are developing prototype control station with various operator interfaces. A neural-network based vision system has been implemented to aid in the precise positioning required for truss node attachment. The SM^2 has demonstrated its ability to walk reliably to any unobstructed external area of the truss. The SM^2 control system includes the hierarchical control structure which allows control to be executed in four different levels autonomously or by teleoperation, the multi-phase control strategy which facilitates the control in different tasks, and various robust low-level controllers.

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