Embedded Real-Time Linux for Cable Robot Control

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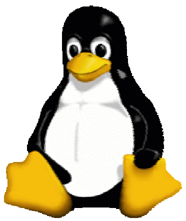
Linux



- Linux is a Unix clone, written by Linus Torvalds at the University of Helsinki
  - begun in 1991, version 1.0 released in 1994
  - full-featured Unix: protected mode, multiprocessing, multitasking, virtual memory, shared libraries, networking
  - available for 386 and higher processors, Compaq Alpha, Sun SPARC, Motorola 68K and PowerPC, ARM, MIPS, more
- Linux source code is freely available as Open Source under the Gnu General Public License
- Many companies sell pre-configured distributions: Red Hat, Mandrake, Caldera, SuSE

Embedded Linux

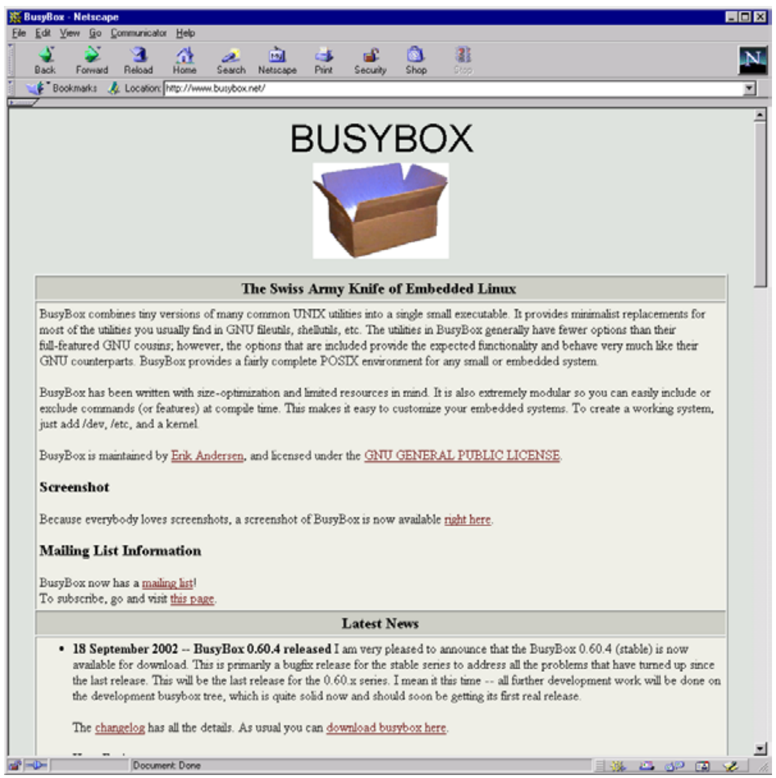
- Free and portable, Linux is popular for embedded systems
  - highly customizable for minimal use of computing and power resources
  - ability to run from ROM, Flash with no rotating media
- Linux supports soft real-time execution
  - tasks that can tolerate some variation in execution time
  - no requirement for completion before a deadline
- Linux doesn't support hard real-time execution
  - optimized for best average response time
  - can't guarantee task execution by a deadline, even for interrupt-based device drivers

Real-Time Linux

- Changes to Linux scheduler for real-time operation are available, and free
  - RTL from New Mexico Tech: X86, PowerPC, Alpha
  - RTAI from Milan Polytech: X86, PowerQUICC
- RTL and RTAI provide similar mechanism
  - RT scheduler runs RT tasks first
  - Linux is run as the last task, and is preempted for RT tasks
  - RT layer captures and defers interrupts to Linux device drivers
  - RT layer dispatches interrupts to RT device drivers as usual
- Your RT software is effectively a real-time device driver, with shared memory or FIFO communication to non-real-time Linux processes

Embedded Linux Distributions

Dozens of embedded Linux distributions are available



We selected BusyBox, distributed free as open source

Diskless Operation

- For applications that experience shock or vibration, solid-state read-write media is a must. Some alternatives:
  - Compact Flash, with built-in IDE interface for direct disk replacement
  - DiskOnChip, which requires newer Linux 2.4 kernel Memory Technology Devices (MTD) subsystem, device drivers
- Write operations wear out Flash media
  - "wear leveling" spreads out write operations transparently, lengthening lifetime to hundreds of years for typical use
  - achieved through either file system layer (e.g., Journaling Flash File System (JFFS)) or on the chip itself (e.g., DiskOnChip TrueFFS)

Booting

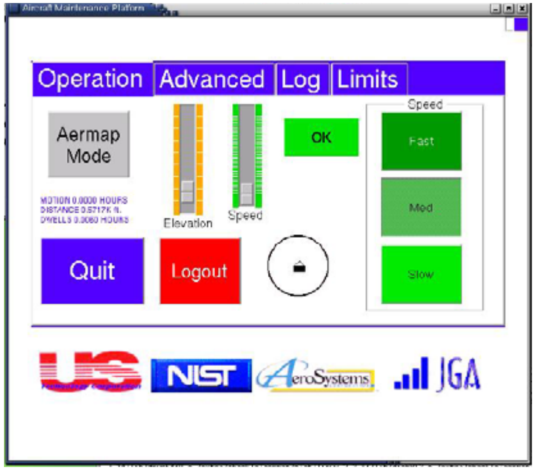
- Booting from IDE-emulating Flash is automatic
  - IDE interface makes Flash look like a normal disk
- Non-IDE flash requires additional software
  - for DiskOnChip, doc-lilo is needed
  - RAM disk image holds compressed Linux kernel and some boot files; you create this off-line and load into Flash
  - doc-lilo reads from Flash, loads RAM disk image, and booting continues as usual
- Linux supports RAM disks for files that do not need to persist between reboots, e.g., log files

Booting

- For instant-on applications, PC BIOS self-test and generic device initialization can be replaced with LinuxBIOS
  - project originated at Los Alamos National Lab
  - Linux boots from cold start to prompt in a few seconds
  - requires a specific port of LinuxBIOS to your PC board
- For networked applications, Linux can be configured to use BOOTP
  - commonly used for rack-mounted clusters
  - saves media cost, simplifies kernel upgrades

Graphics support

- Linux typically uses the X Windows graphics system
  - takes tens of megabytes of disk, megabytes of RAM
- Stripped-down alternatives exist that still support mouse input and multiple windows
  - GGI, DinX
  - MicroWindows/NanoX
  - Qt/Embedded ⇒



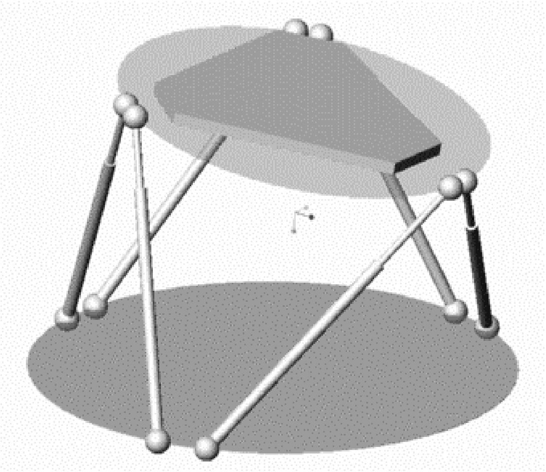
- These use either video board-specific libraries, the SVGA standard, or the newer Linux Frame Buffer abstraction
  - the Frame Buffer has been ported to many modern boards, and supports higher resolution, more colors

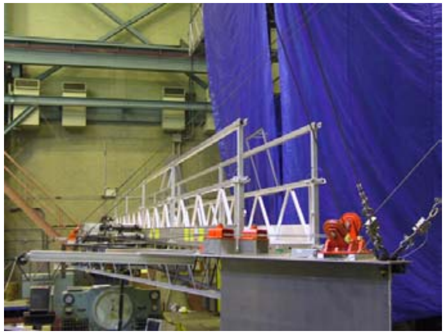
Configuring Embedded RT Linux

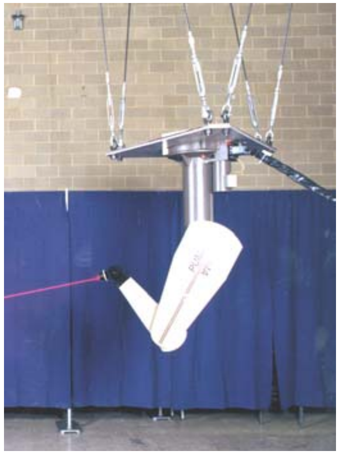
- Set up a conventional development system with hard disk, floppy, CD-ROM, etc. and RT Linux source code
  - follow instructions provided with plain vanilla Linux, RT Linux distributions
  - build a bootable RT Linux kernel, including Memory Technology Devices subsystem, Flash disk drivers
  - build a bootable floppy with this kernel, additional floppies with useful utilities
- Boot embedded system off the floppy
  - use utility floppy to format flash disk, copy kernel and boot loader
  - Copy your application code to Flash as it evolves
- Other options: development system = embedded system; networked embedded system

Cable Robots

- Stewart Platform parallel kinematic mechanism turned upside-down
- Cables instead of linear actuators
- Quite stiff, and improves with loading
- Dual of serial kinematic mechanism: inverse kinematics are closed form (easy), forward kinematics are iterative (hard)

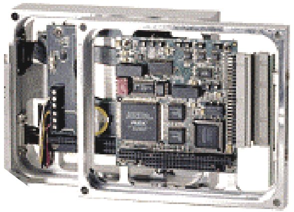




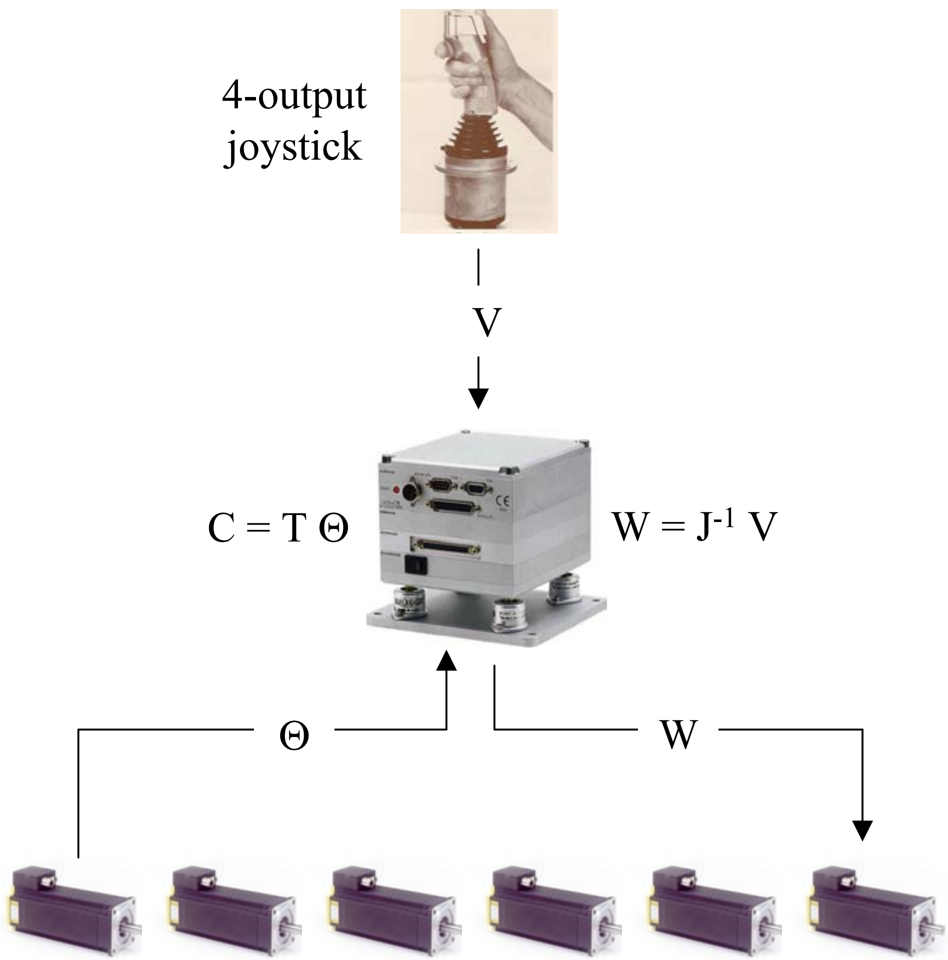


Our Computing Needs

- Solid-state media for shock- and vibration resistance
- Real-time control for Cartesian velocity teleoperation
- Bi-directional serial I/O to digital motor controllers
- Analog input, digital I/O to sensors and relays
- Our system:
  - PC-104 with Pentium Geode processor
  - BusyBox Linux, New Mexico Tech RTL
  - DiskOnChip 96 Mb Flash
  - Qt/Embedded, Touch screen w/ custom driver
  - RS-232/422 serial; analog input, digital I/O
  - Ethernet for development



Cartesian Teleoperation



- Joystick outputs XYZ-Yaw velocities; Roll and Pitch set to zero
- Controller transforms to cable velocities using inverse Jacobian J^{-1}
- Cable velocities sent to motor controllers via RS-232,422 serial links
- Motor controllers reply with rotational positions ($\Rightarrow$ cable lengths)
- Controller transforms to Cartesian position using forward kinematics T
- Repeat next Δt ...
- Note: J^{-1} is an instantaneous relationship; for finite duration between commands some roll and pitch velocities will creep in

Automatic Leveling

$$\begin{bmatrix} \\ \\ J^{-1} \\ \\ \\ \end{bmatrix} \begin{bmatrix} V_x \\ V_y \\ V_z \\ V_r \\ V_p \\ V_w \end{bmatrix} = \begin{bmatrix} \omega_0 \\ \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \\ \omega_5 \end{bmatrix}$$

$\Rightarrow$ . . . $\Rightarrow$

$$\begin{bmatrix} \\ \\ T \\ \\ \\ \end{bmatrix} \begin{bmatrix} \theta_0 \\ \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \\ R \\ P \\ W \end{bmatrix}$$

Synthetic leveling: roll and pitch are computed from T;

$$V_r = -k\, R_{computed}\,,\quad V_p = -k\, P_{computed}$$

Sensor leveling: sensor produces outputs proportional to roll, pitch;

$$V_r = -k\, R_{meas}\,,\quad V_p = -k\, P_{meas}$$

Automatic Leveling

- Synthetic leveling:
  - no need for separate sensor
  - can't compensate for cable sag, uncalibrated kinematics
- Sensor leveling:
  - a true measure; compensates for cable sag, uncalibrated kinematics
  - requires a separate sensor and associated computer inputs
- These can be combined to detect sag outside some allowable range, or cable interference
- Both methods are closed-loop, and require tuning of gains
  - simple proportional (P) control worked fine
  - PID can clean up steady-state error, damp response

Calibration and Homing

- Calibration of cable robots is difficult
  - large structures present accessibility problems
  - pulleys spread as the platform rises
  - effective cable drum diameter changes as cable wraps up
  - net result: accuracy on the order of centimeters over 10 meters
  - during teleoperation, people will accommodate for this
- A homing procedure is necessary
  - since the forward kinematics are iterative, we need a good estimate of the initial Cartesian position for measured cable lengths
  - from scratch, we define a Cartesian home position with respect to world coordinates; run inverse kinematics to get cable lengths
  - if the robot is not homed the cables must be jogged to their home lengths, which should be marked for convenience
  - during routine operation, we save Cartesian position to Flash at shutdown and restore at startup, allowing power-down anywhere

Summary

- Linux is a free operating system with embedded- and real-time distributions, useful for research and commercial applications
- Solid-state replacements for rotating disk storage protect against shock and vibration, making robust systems
- Sophisticated graphical user interfaces can be built with modest storage and memory requirements
- We built a cable robot controller using the PC-104 form factor, DiskOnChip Flash media, and free software
- Cartesian teleoperation using non-trivial kinematics was accomplished successfully