Making your own RCX-sensors (Part II)

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In the first part we presented advanced applications of standard LEGO sensors. The following pages will explore the large field of non-LEGO devices. But, before talking about such electronics circuits, it is important to understand how they can be interfaced to the RCX. It is therefore essential to scrutinize the functionality of RCX input ports.

1. RCX analog input

The heart of the RCX is a Hitachi H8/3292 microcontroller. Internally this powerful chip is composed of a microprocessor and a set of periphery devices that are destined to communicate with the outer world. For instance, the H8 includes a serial communication device that allows networking with the PC and other RCXs. You also find a clock generator that produces the required system beat. There are output ports to control the motors, the display, various internal circuitries and the loudspeaker. There exist digital input lines intended to extract the information from the RCX buttons. But, in the center of interest of this paper, we will consider the analog input ports that make sensor data directly readable by the RCX. In fact, to be able to extract the information from an electric voltage, the RCX uses special H8-devices that are called analog-to-digital (A/D) converters[i], which –as the word suggest- transform input-voltages into digital numbers. By this way, 0V correspond to digital value 0, and 5V are read as 1023 (=2^{10}-1). With the comfortable 10-bit resolution, the RCX is able to distinguish voltages that only differ by 5/1023 =4.88mV !!
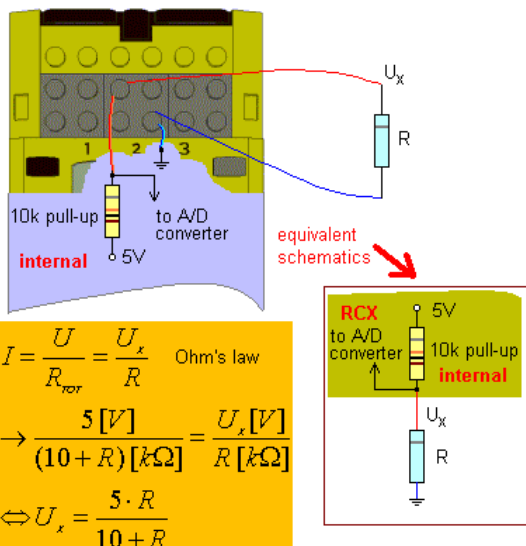
At reboot, the RCX runs a very basic program called the executive that among many other things configures the analog input lines 1, 2 and 3 as "unpowered" sensor ports. After downloading the RCX firmware or after switching the RCX off and on, the sensors are reset to this initial configuration. The qualification "unpowered" may sound confusing, because an applied voltmeter measures 5V at each port. But it makes the distinction to another sensor-port configuration, declared as "powered", that instead produces around 9V. The "unpowered" configuration is needed for the original LEGO touch sensor and the temperature sensor, whereas the "powered" setup is required for the light and the rotation sensors.

1.1. "Unpowered" sensors

Picture 1: Paradoxically "unpowered" sensor ports present a voltage of 5V.

The most important differences between the two sensor classes are that "unpowered" sensors normally are made of passive only electronic parts – in fact pure resistive elements – while "powered" sensors additionally use active parts – transistors, diodes, opto-elements or integrated circuits - that need significantly more electric current. The maximum current that may be drawn by "unpowered" sensors is 0.5mA. By contrast, "powered" sensors are able to draw as much as 15mA.

$$I = \frac{U}{R_{TOT}} = \frac{U_x}{R} \quad \text{Ohm's law}$$

$$\rightarrow \frac{5\,[V]}{(10+R)\,[k\Omega]} = \frac{U_x\,[V]}{R\,[k\Omega]}$$

$$\Leftrightarrow U_x = \frac{5 \cdot R}{10+R}$$

Picture 2: "Unpowered" configuration[ii].

What happens, if we connect a 10kOhm resistor to an "unpowered" sensor port using crocodile clips? Picture 2 formula tells us that the voltage will drop from 5V to Ux = 5*10/(10+10) = 2.5V, the equivalent of raw sensor-value 511[iii].

Picture 3: A 10kOhm resistor with crocodile clips.

It could be an excellent exercise to try various other resistors, to write down the RCX corresponding raw-values and to draw a function graph. You will note that the RCX raw-values don't evolve proportionally in function of the resistor-values and you'll learn that the relationship between the displayed RCX values and the resistor-values is based on Ohm's Law for resistors in series.
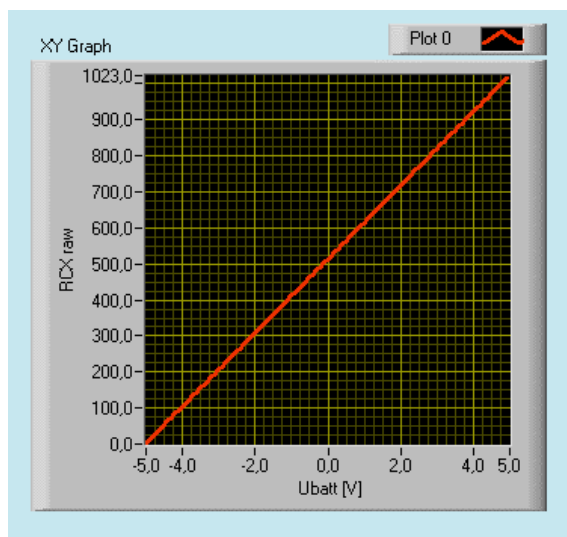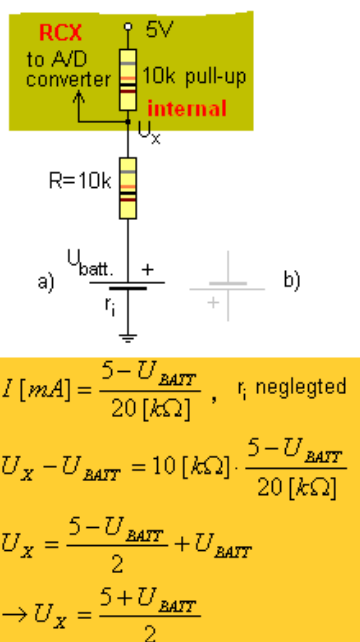
Any pure resistive device can be used as an "unpowered" sensor. Some commonly used parts are:
- ✓ Potentiometers – to measure angles
- ✓ Resistive temperature sensors
- ✓ CdS light sensors

Pictures 4 & 5: Example of a resistive sensor : a potentiometer measuring angles that may easily be hidden into a LEGO brick and equipped with a gear. Unfortunately the original LEGO connector must be cut and soldered to the pins of the variable resistor.

"Unpowered" sensor ports also can read voltages. If we consider the resistor-circuit above, electric current is only flowing from the sensor port + to Ground (Gnd) through the resistor. But if - for example - an external battery is wired to the port, things change a lot, because additional power is added to the RCX circuitry.

$$I\,[mA] = \frac{5 - U_{BATT}}{20\,[k\Omega]}\,, \quad r_i \text{ neglegted}$$

$$U_X - U_{BATT} = 10\,[k\Omega]\cdot\frac{5 - U_{BATT}}{20\,[k\Omega]}$$

$$U_X = \frac{5 - U_{BATT}}{2} + U_{BATT}$$

$$\rightarrow U_X = \frac{5 + U_{BATT}}{2}$$

Pictures 6 & 7: This assembly allows measurement of voltages. The response is very linear (under the condition that the internal resistance of the external voltage source is very small.) Note that due to the external additional 10k resistor, negative voltages may also be read.

1.2. "Powered sensors"

Things are a bit more complicated for "powered" sensors, but they are still based on the same principles. The RCX inventors worked hard to ensure that the input ports were flexible and secure. Obviously they imposed some important constraints considering future RCX consumers. The engineers realized that children playing with the RCX would use the sensors in new and unpredictable ways. Many questions must have appeared: Could kids damage the RCX, if they directly connected a motor-output to a sensor port? Or, if they wired an input-line to an external battery package? What if they short-circuited the input?

The LEGO engineers needed to protect the internal micro-controller from high voltage or wrong polarity, without disturbing any of the desired sensor-functions. But, perhaps the most challenging exercise was to imagine a two-wire connection able to transport both the analog signal and the power-supply for the "powered" sensors. In fact, the RCX would have become a rather poor device, if its inventors only had allowed passive analog voltage readings. As pointed out, in order to include resistor-measurements for instance, they added a 10k pull-up resistor to each A/D-channel, leading 5V to the sensor input. However the weak current that the port could deliver now, hardly was sufficient to power any external electronics. Therefore a further micro-controller pin was engaged for each sensor to switch a transistor capable of draining much higher currents at full battery voltage through an additional protection resistor.

The micro-controller was programmed to alternatively switch on and off the transistors via H8 Port6, pin 0..2, configured as outputs. The idea was on the sensor side to charge a capacitor –an electronics device comparable to a rechargeable battery with extremely high charging speed- during the high voltage (and low impedance[iv]) phase, which then would hold the voltage during the much shorter high impedance period, where the A/D-converter becomes active. There had to be a trade-off between highest sampling rate, signal stability and maximum current, expressed in the duty cycle of the sensor output. The best choice compared to the general firmware-features seemed to be 3ms to 0.1ms, representing a duty cycle of 3 / 3.1 = 96.7%. The maximum current now was 15mA, largely enough to power simple active sensors. The sampling rate of about 300Hz also was acceptable for the original LEGO powered sensors, especially for the LEGO rotation sensor, which should at least be able to read rotations at the LEGO geared motor speed of 350 rpm.
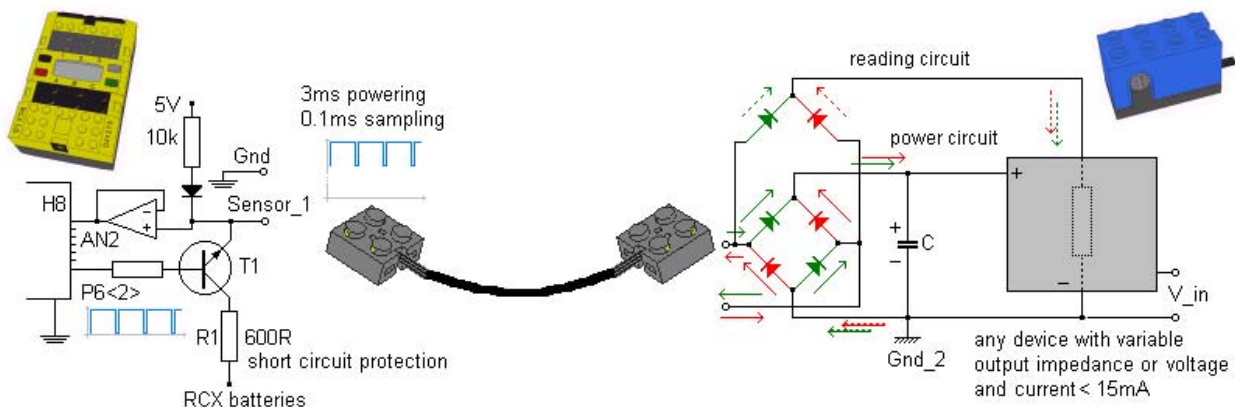
Picture 8: Roughly equivalent diagram representing the "powered" configuration. Depending on the LEGO connector orientation, the current will either follow the red or the green way.

From the "powered" sensor point of view, it must be underlined that the capacitor C has been sufficiently charged during the 3ms powering period. In the following 0.1ms "reading or sampling phase", the sensor doesn't receive its power from the RCX anymore, but is forced to live on the resources that have been accumulated in the capacitor. The diodes in the rectifier bridge are very important in that phase to prevent current from flowing into the wrong direction during that phase and be lost for the sensor. The reading circuit however follows the powering down of the RCX port to the level given by the sensor output. Thus the sensor may then be considered as a kind of active resistor with sensor input controlled resistance (or impedance), which will be read by the RCX as if it were an "unpowered" device. Note that the standard RCX firmware reads "unpowered" and "powered" sensors exactly at the same rate.
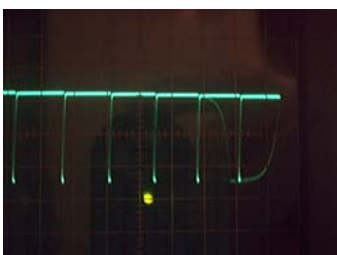
Picture 9: Oscilloscope screen-shot of the "powered" sensor signal.
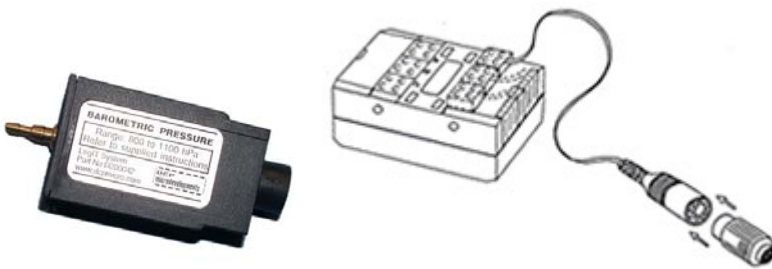
2. LEGO compatible sensors

We now will present a few remarkable third party RCX compatible sensors that may be separated into two major categories:

- ✓ Professional and buyable sensors
- ✓ Amateur, homebrew or study sensors

2.1. Professional sensors

There are various producers who are offering RCX extending sensors:

- ➢ The official LEGO partner **DCP microdevelopments** (http://www.dcpmicro.com/lego/index.htm) provides a series of well-designed LogIT sensors that are easily connectable to the RCX using the DCP adapter. ROBOLAB includes sensor drivers for each of them. This makes their manipulation very comfortable. Most of the sensors are laid out to measure physical or chemical data like pH that rarely appear in robot projects, but rather in those projects, where the RCX is used as a datalogger.


Pictures 10 & 11: The DCP barometric pressure sensor and the DCP adapter.
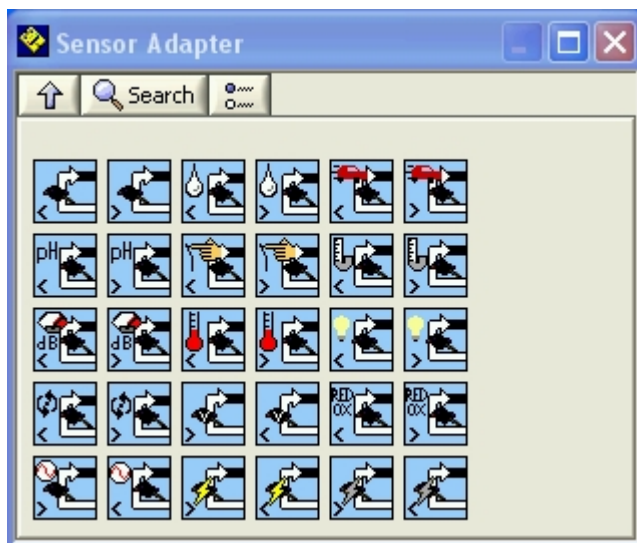

Picture 12: Some ROBOLAB DCP sensor driver sub.vis.

- ➢ Pete Sevcik[v] has founded a company named **techno-stuff robotics** (http://www.techno-stuff.com) that offers a very interesting set of RCX compatible sensors. Unfortunately Pete doesn't refer to ROBOLAB drivers yet, but for medium skilled programming minds it should be no problem to develop own ones. **Techno-stuff** sensors are specially destined for mobile robots.
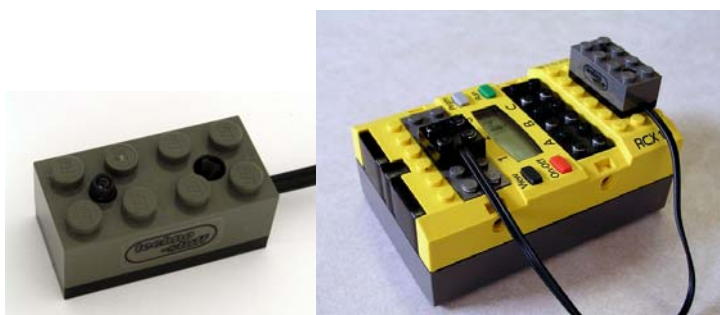
Pictures 13 & 14: Techno-stuff's infrared distance sensor

> ➢ **Hitechnic** (http://www.hitechnic.com/) offers a list of very sophisticated sensors like a 5° precise electronic compass. The sensors are easy to operate with the existing RCX sensor configurations. They are specially useful in mobile robotics.
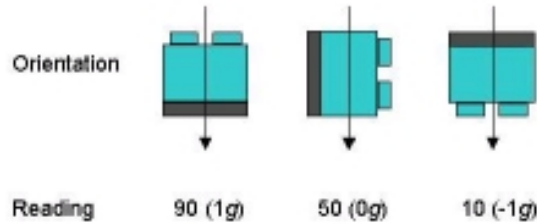
Pictures 15 & 16: Hitechnic's accelerometer

> ➢ **Mindsensors** (http://www.mindsensors.com/) sells very impressive RCX compatible devices -many of them intelligent, e.a. microcontroller equipped- with the remarkable feature that no additional adapters are required.

Pictures 17 & 18: Mindsensors' ultrasonic distance sensor.

While thinking of enlarging the RCX sensor palette in order to increase the number of robot-possibilities, one often has to weight prices against costs in terms of building time, required skills and additional material or tools. Ready from the shelf sensors possess the great quality of being ready for use in the sense of plug and play. Mostly the hardware and software interfacing is well designed and, luckily, bad surprises are rare. However, the given sensor might not completely fit for the specific application, or there could be a serious matter of $ or € In those cases, the search for a suitable sensor should be extended to the next category of devices, which are:

2.2. Amateur sensors

These sensors mostly are the products of engaged leisure time engineers or students that want to unlock some special feature of their current robot project. The sensors generally exist as unique prototypes, sometimes on breadboard only, often on pre-perforated PC boards and rarely on etched circuits. While breadboards have the advantage of flexibility and re-usability, PC board sensors are soldered, may be fixing expensive electronics parts in a particular project. However, PC boards are very compact compared to the spacey breadboard-layouts. Many people share their designs through the web, via articles, or even books, so that other electronics hobbyists can reproduce them, which isn't evident at all in most of the cases, because of unexpected behavior due to part differences, stray capacitances, or even design errors that didn't produce any noticeable effect in the original model.

There exist low-level passive sensors that are very easy to copy. Active transistorized circuits are much more sensitive and require already serious skills in building electronics. Intelligent, microcontroller equipped designs are very hard to reproduce, due to heavy prerequisites like the processor-specific programming apparatus or the related compiler software. Often, trying to rebuild one of these more complex sensors lets the copier rather frustrated, because there is an obvious risk that something is going wrong during the rebuilding procedure… and Murphy's Law is very skeptic here. Nevertheless, this kind of experiencing is very challenging and the best occasion of learning about micro-electronics.

Besides our own well-known web-site http://www.convict.lu/Jeunes/RoboticsIntro.htm we want to pick out the best repertory of reproducible homebrew sensors which is Mike Gasperi's excellent web-collection: http://www.plazaearth.com/usr/gasperi/lego.htm and perhaps the most remarkable site of the genius French Mindstormer Philippe Hurbain: http://philohome.com/sensors.htm . These sites certainly are the most visited in the particular field of homebrew RCX compatible sensors. Note that the described sensors sometimes are quite complicated, but generally very reliable. Besides these outstanding web-places, there exist a huge number of small application-sites presenting more or less clever solutions that could be exactly what you need for your current robot project. However, as already pointed out, there is a certain risk that the sensor could not behave exactly as the author affirms or as you expected. There also could be more serious incompatibility problems or software driver difficulties that are not easily solvable. Reproducing these sensors

may be excitingly adventuresome. Directly contacting the author or asking pertinent questions in a web-ring can facilitate the realization a lot.

To illustrate a typical breadboard sensor, have a look at Mike Gasperi's famous color-sensor that has been the subject of an article in the *Nuts and Volts* journal:
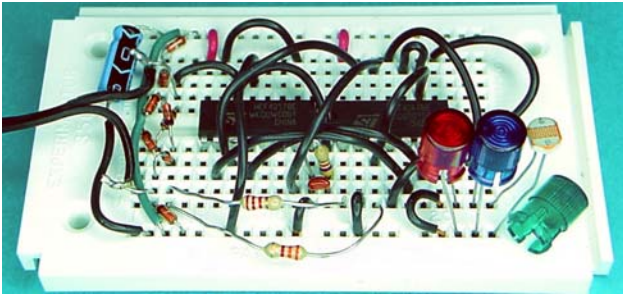
Picture 19: Breadboard color-sensor prototype. Note the 3 CdS light sensitive sensors - the green one being uncovered-. (Photo: Mike Gasperi)

The corresponding pre-perforated PC board has the following aspect:
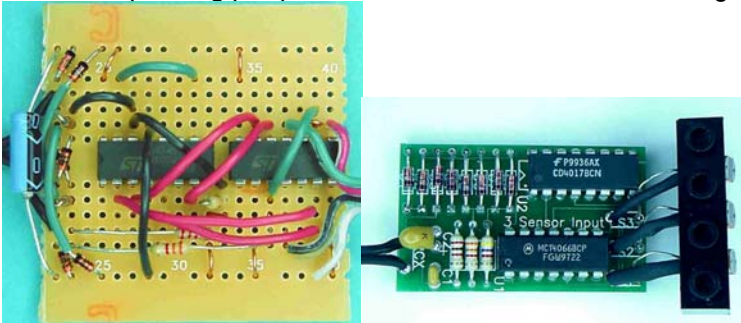
 (Photos: Mike Gasperi)

Pictures 20 & 21: The same sensor parts soldered on a through hole type circuit board and the compact professionally etched PC board.

Two further excellent breadboard examples can be found in Brian Bagnall's book *Core LEGO Mindstorms Programming*, USA 2002. (Brian is co-author of the leJOS Java Virtual Machine).

The most challenging activity however is the complete inventing of a new sensor. That kind of exercise only is possible in a well-equipped electronics laboratory under skilled guidance. For the purpose note the recommendable boards that are being sold by www.mindsensors.com [vi] :
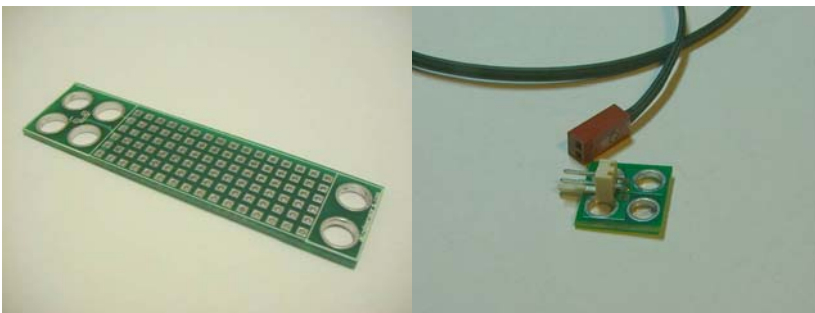
Pictures 22 & 23: Two very practical boards that can be used for sensor prototyping from www.mindsensors.com .

(One nasty problem must be pointed out. As practical as the LEGO connecters are for normal sensor wiring, as complicated they may become with homemade sensors. Either one has to sacrifice an original LEGO connector, or one has to start improvising with adapters.)

3. Building your own differential light sensor

We now propose to reproduce a very useful sensor that has been developed for mobile indoor robotics. The presented sensor has a long history. A first layout appeared rather early as one of Mike Gasperi's first realizations. Later Mike published the circuit in the famous book *Extreme Mindstorms*[vii]. This present 3d issue adds some significant changes to the original design.

Imagine that you want to realize a robot that should be able to find or even to track a light source. A common solution for this robot-challenge is to have the robot sweep back and forth over a certain range in order to have a light sensor detect a light-intensity maximum somewhere. (This sweep strategy is also applied in line-following robots that are only equipped with one light sensor.) Another more sophisticated solution is to use two photo sensors instead of one and to continuously compare both measured sensor-values. The robot

brain then decides either to turn its base to the left or to the right, depending on which sensor measured the highest value. The robot should move straight forward, if both values are sensibly equal. The advantage of this solution is the fact that the robot doesn't need to execute a sweep movement all the time, because it can compare synchronously read data. The disadvantage is that two RCX ports are condemned.

A better solution is to directly measure the difference between two separated light-detectors and convert this difference to a voltage that is read by one only RCX input port. That's exactly the sensor-solution that we want to present in the following.
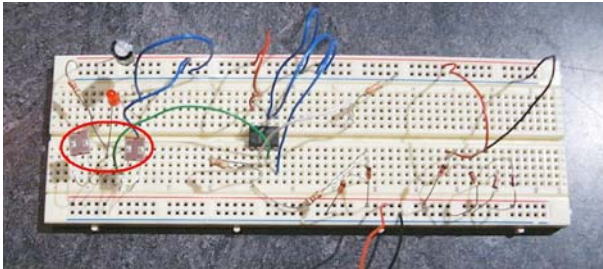
Picture 24: Differential light sensor prototype. (Both CdS photo-resistors have been marked.)

The heart of this sensor is a LM358 operation amplifier stage. Its function is first to buffer the relatively high impedance signal that is produced in the photo-sensor bridge and led to the op-amp input. Note that for the sake of linearity response, in any case the sensor output should be as low impedance as possible. The CdS-sensor-bridge generates a voltage that is only dependent on the difference of light intensity that may exist between the two CdS plates. Small variations of the ambient light are directly eliminated in the circuit, because they don't affect the ratio of both sensor CdS-sensor resistances.

The second function of the op-amp is a weak amplification and a voltage shift that is needed to fix the sensors middle position to a voltage that corresponds to RCX sensor value 50 (percent mode). Both the shift and the amplification are the result of the resistors 47k and 33k. The functions of the diodes and the capacitor have been explained above.
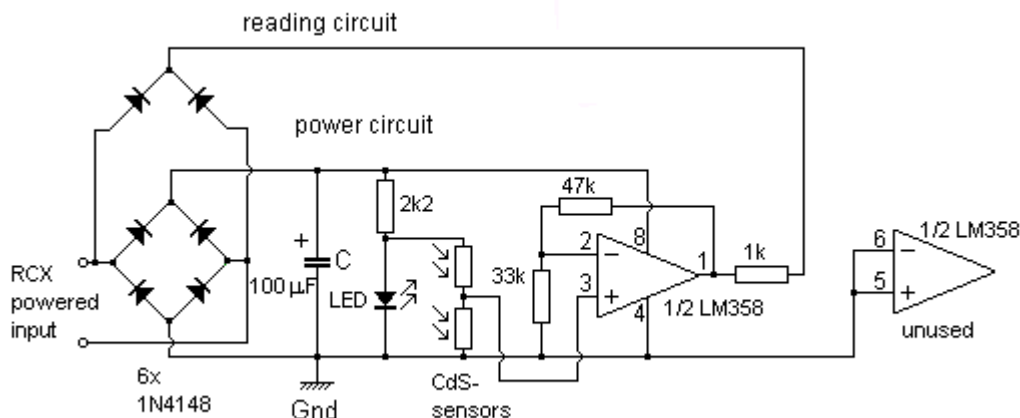
Picture 25: Complete diagram of the RCX compatible differential light sensor.

The output resistor's value (1kOhm) has been chosen in relation to the conversion that the RCX firmware applies to transform sensor raw values into percent values. The rules for this conversion have been defined by the original LEGO light sensor adaptation. The red LED (low-current type) is used for three reasons. First, obviously, it serves as an indicator that the device is correctly powered. Second, it may be used as a weak light source for special sensor applications. Finally –a bit more difficult to understand – it helps regulating the op-amp reference voltage. This is necessary, because the sensor might not receive the same supply voltage all the time due to battery weakness. If the reference voltage wasn't regulated, the sensor would present a significant drift, which means that, under a certain illumination, the RCX raw values would not have the same intensity. The result were that it would be necessary to reprogram the RCX with new threshold values over and over again. The applied regulation trick is that a LED produces an astonishingly constant forward-voltage drop around 1.7V. So, independently of the source voltage, the reference voltage always is 1.7V.

The chip LM358 is composed of two independent op-amps that are exposed to the same supply lines. Therefore it is important to pull-down both inputs of the unused stage to prevent the device from "floating", which is an uncontrolled high frequency oscillation.

One word concerning the capacitor value C: there often is a confusion about the dimension of this part. But the capacity may easily be yielded through the following formula:

$$T [\mu s] = Z [k\Omega] * C [\mu F],$$

Where Z is the device impedance and T the device time constant.

We consider T=0.1ms = 100μs corresponding to the RCX sensor reading time, during which the capacitor should maintain the sensor supply voltage. Z may be deduced, if we measure the current that is passing through the sensor (in our case 8mA) :

$$Z = U / I = 9 [V] / 8 [mA] = 1.125 [k\Omega],$$ according to Ohm's law.

Now C can be calculated:

$$C = T / Z = 100 [\mu s] / 1.125 [k\Omega] = 89 [\mu F].$$ Since there doesn't exist any standard electrolytic capacitor with that value, we must choose the next possible, which is 100μF. Note that this capacity guarantees a voltage stability of 0.1% which is close to the 10-bit RCX sampling resolution.

Driving the sensor is most simple, because the returned values are completely compatible with RCX percent mode. The sensor only needs to be configured as a standard LEGO light sensor. If the sensor notices differences of light intensity, the values will drop beyond the middle position with the range 0..100%. Thus, values 0...49% could indicate that the left CdS-photocell is in a brighter area than the right; vice-versa: 51..100%. However, part differences, especially due to resistor tolerances, may shift the middle position of your particular sensor to another value in the range of 45..55%.

Note that the RCX percent mode is defined by the following formula that is applied to integer data:

$$X[\%] = (1023-raw) * 25 / 156$$

Raw values < 392 are converted to percent value 100%

As the result of the 1k resistor and the presence of 2 diodes in the "reading-circuit", the sensor output voltage never may be less than 1.9V corresponding to RCX raw-value 392 !

The advanced user could write his own conversion function and include it in his programs to obtain better values, in the case of too an important shift.

In practice, breadboard-sensors are difficult to integrate into a real robot-project. Mechanical vibrations could generate loose contacts. There also is a serious risk of short-circuits. Therefore it is a good idea to find an experienced electronics specialist who may help realizing a solid-state soldered PC board. (Radio amateurs are known to be very gifted for that kind of exercise.) Often the attempt to reduce the sensor size as much as possible is in the center of interest. The real dimensions of the following PC board are 2 x 3cm only ! The electronic parts are held in SMD-technology. Soldering these parts is reserved for skilled hands only –but still in the reach of the hobbyist.
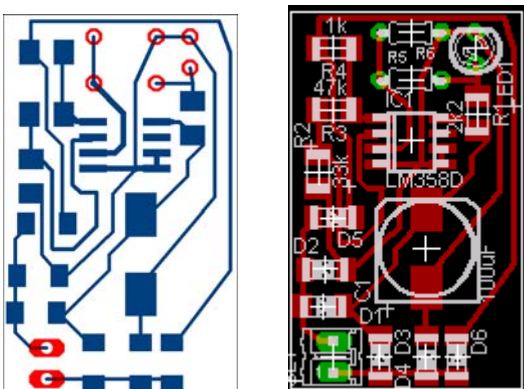
Pictures 26: Enlarged layout of the SMD PC board.

4. Conclusion :

Extending the RCX sensor set either with professional or amateur devices is a very exciting field that will enlarge the possibilities of advanced robot-projects. New skills can be learned and exercised. New challenges can be faced.

Glossary: Resistor: An electronic component that opposes resistance to electric current at a known degree is called a resistor. There exist various package forms and as many physical constructions. Current flowing through a resistor causes the device to heat. Thus electric energy is dissipated in a resistor in the form of heat. Ohm's Law states that when a certain voltage is applied to a resistor, the current that is drawn through it, is directly proportional to the applied voltage and inversely proportional to the resistance:

Ohm's Law :   U [Volt] = I [Ampere] * R [Ohm]
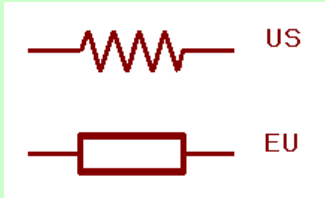
Usual resistor symbols
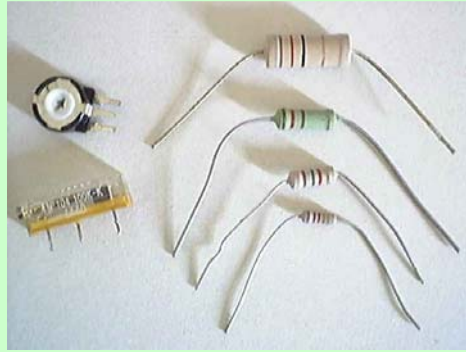
Different resistor packages (1/4W, 1/2W, 1W, 5W). On the left side two variable resistors also called potentiometers.
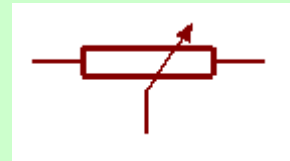
Potentiometer symbol
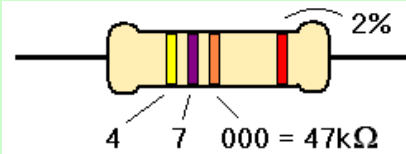
How to determine the resistance from the color code.

| Color	1t color ring	2d color ring	3d color ring	Tolerance
black	0	0	-	
brown	1	1	0	
red	2	2	00	
orange	3	3	000	
yellow	4	4	0000	red 2%
green	5	5	00000	gold 5%
blue	6	6	000000	silver 10%
violet	7	7		
gray	8	8		
white	9	9		

Glossary: Capacitor: Two parallel plates, placed close to each other, only separated by a medium called dielectricum, can store a certain quantity of electricity, when a voltage is applied to them. The fundamental equation states that the electric charge is proportional to the voltage and the capacitance:

Q [Coulomb] = C [Farad] * U [Volt]

The most usual units are :
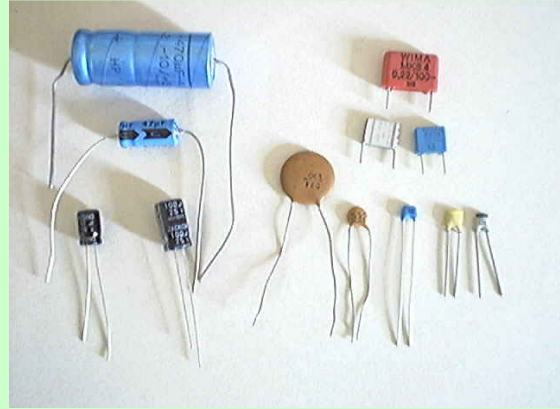
- microfarad mF = 10^{-6}F
- nanofarad nF = 10^{-9}F
- picofarad pF = 10^{-12}F

Capacitors exist in many forms and constructions. Special attention has to be paid to electrolytic capacitors (polarity and maximum voltage ratings.)
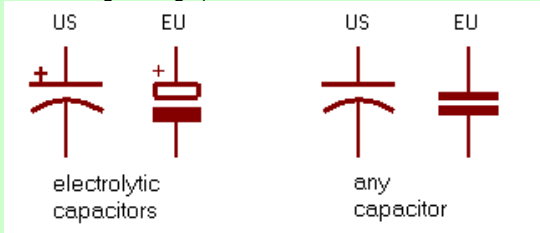

Capacitor symbols

Some capacitor packages.
The capacitance-values are normally printed on the device packages. But there are various forms, that a skilled eye knows to interpret together with the device-dimension. examples:

- .068 = 0.068 mF
- 103 = 10E3 pF = 10nF
- 104 = 10E4 pF = 100nF
- 4p7 = 4.7 pF

Sometimes a color code is used too.

Glossary: Diode: Semi-conductor diodes have completely replaced vacuum-tube diodes. Solid-state diodes are much smaller, they do not need filament heating and thus consume much less power ; they can be operated at very high frequencies. However their function remains the same: placed in their conducting direction, they allow current to flow, while on the contrary no current is drawn.


Anode   Cathode
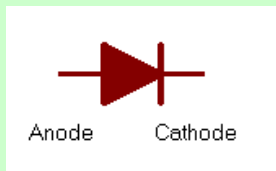
Diode symbol
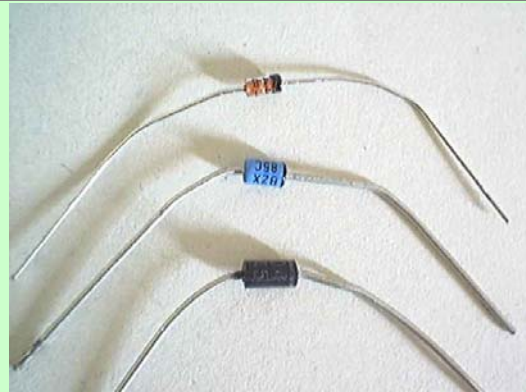
Some solid-state diode packages.

Glossary: Transistor: The word "transistor" was chosen to describe the new three-terminal device that is able to amplify signal energy. Its characteristic function is one of "transferring current across a resistor". The transistor is a three pin electronic device that works as a variable resistor whose value may be current-controlled. Invented in 1947 by Shockley, Bardeen and Brattain at Bell Labs, it rapidly replaced the vacuum triodes, because of many advantages such as low current-consumption, high frequency features and small physical size. Compared to the physics behind, its function is rather easy to understand. If a voltage is applied to the *collector* (C) and the *emitter* (E), the current that flows through the device largely depends on the voltage at the *base* (B). If the voltage $U_{B(ase)E(mitter)}$ is less than the characteristic semi-conductor threshold (for Silicium 0.6V), no current is drawn at all. Above this cut-off voltage the current $I_{C(ollector)}$ rapidly grows with rising U_{BE}. It is apparent that very weak variations of U_{BE} (and consequently I_B) cause strong variations of I_C.
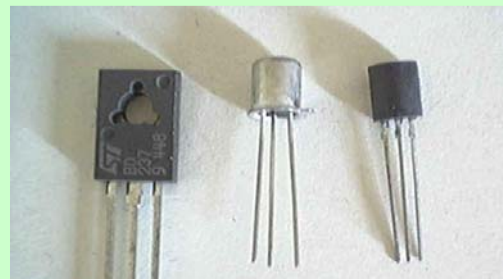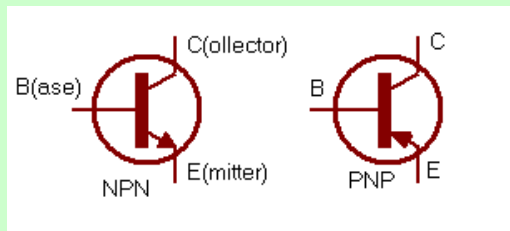
Bipolar transistor symbol

Glossary: Op-amp: Operation amplifiers are integrated transistorized devices with many features :

- linear response over a large voltage range (if the range extends over the whole supply voltage, one speaks of a rail-to-rail op-amp)
- good frequency response
- high input impedances
- low output impedance
- high gain
- low power consumption
- easy to calibrate
- small dimension
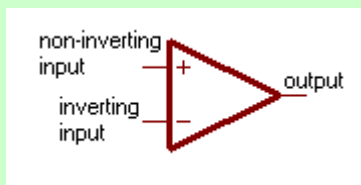
Op-amp symbol
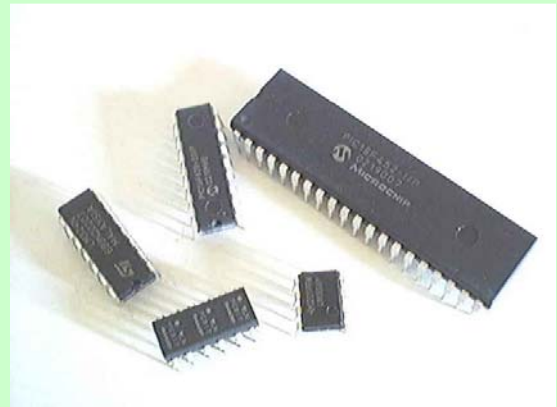
Some IC packages.

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[i] A/D-converter: An analog-to-digital converter (ADC) is an electronic device capable of transforming a physical voltage into a digital number. An ADC is mainly characterized by the sampling rate (a direct function of the conversion time) and the dimension of the returned number expressed in bits. The device always needs reference voltages defining the operation range. The digitized signal is a discrete function of time that is slightly diphased in comparison to the original signal. Many micro-controllers have on-board ADC channels that can be individually configured. The Hitachi H8, the heart of the RCX, disposes of eight ADC channels. The RCX only uses four, three of them represent the sensor inputs and the fourth the battery level measurement system.

[ii] Pull-up / pull-down resistors: These resistors (generally 3-10k) are often used to control inputs. If the input-source is not actively generating a signal or if there is no source at all, the following electronics could start "floating" e.g. oscillating between high and low states. To prevent this effect, one connects the input to the supply via pull-up or to ground via pull-down resistor.

[iii] How to convert voltages to RCX raw values and vice-versa:

$$\frac{raw}{1023} = \frac{U_x[V]}{5[V]}$$

$$\rightarrow raw = 1023 \cdot \frac{U_x}{5}$$

$$U_x = 5 \cdot \frac{raw}{1023}[V]$$

[iv] Impedance: In direct current electronics (DC) Ohm's law states that the applied voltage to a load is proportional to the current that is passing the load-device. The factor of proportionality (R = resistance, [Ohm]) depends on the device characteristics. In alternating current electronics (AC) one distinguishes a second class of load, the reactance, that appears in two forms, the capacitance and the inductance. Both characterize the behavior of capacitors or coils (inductors) to which an alternating voltage is applied. The resulting current is proportional to the reactance, which itself depends on characteristics of the device and on the frequency of the alternating voltage. When a circuit contains both resistance and reactance, the combined effect is called impedance, symbolized by the letter Z (the values are expressed in Ohms). Some confusion about this term may appear because it is often used for circuits that have only resistance or reactance.

[v] Pete attended the ROBOLAB conference in 2004.

[vi] http://www.mindsensors.com/index.php?module=pagemaster&PAGE_user_op=view_page&PAGE_id=39&MMN_position=13:13

[vii] *Extreme Mindstorms*, USA 2000, pp 263